THE FUTURE OF THE U.S. MILITARY IN SPACE

by

KEVIN B. OLIVEAU

SUBMITTED TO THE DEPARTMENT OF POLITICAL SCIENCE
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY OF POLITICAL SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1993

© Massachusetts Institute of Technology 1993. All rights reserved.

Author ....................................................

Department of Political Science
June, 1993

Certified by ..............................................

George Rathjens
Professor of Political Science
Thesis Supervisor

Accepted by ..............................................

Donald L. M. Blackmer
Chairman, Graduate Program Committee

ARCHIVES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUL 20 1993
The Future of the U.S. Military in Space

by

Kevin B. Oliveau

Submitted to the Department of Political Science
on June, 1993, in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy of Political Science

Abstract

Today, satellites are performing an ever increasing range of military functions. They act as force multipliers, increasing the effectiveness of forces on Earth. Satellites provide reconnaissance, signals intelligence, communication and navigation on a global scale. As military satellites become more integrated into military operations, military operations without these satellites will become increasing difficult and ineffective.

Satellites have become valuable military targets. This means that in the future the U.S. may need to defend its satellites from enemy attack. The U.S. may also require means of neutralizing hostile satellites.

This dissertation is intended to provide a guide as to what kinds of space systems, both offensive and defensive, the U.S. should be building today and what kinds of systems might be needed in the future. My intended audience is the civilian decision maker. This dissertation has two purposes: to illuminate the nature of war in space and to construct a military space policy for the United States.

Thesis Supervisor: George Rathjens
Title: Professor of Political Science
Acknowledgments

This Dissertation is dedicated to my wife Lauranne.

This research was supported by the Defense and Arms Control Program at MIT, and by Donald and Susan Oliveau. I would like to thank the South Burlington Vermont High School faculty for giving me all the basic skills needed to finish this degree.
Contents

0.1 Glossary .................................................. 15

I  A U.S. Military Space Policy .......................... 19

1 Executive Summary ....................................... 20
  1.1 Designing a U.S. Military Space Policy .............. 20
    1.1.1 Intentions and Capabilities ..................... 22
    1.1.2 The Nature of Space Warfare .................. 23
    1.1.3 Five Threat Levels ............................. 25
    1.1.4 Current U.S. Offensive Capabilities ............ 29
    1.1.5 Biases and Preferences of the U.S. Military Services 30
    1.1.6 Dissertation Road Map .......................... 31

2 The Nature of Space Warfare ........................... 33
  2.1 The Military Importance of Space ................... 33
    2.1.1 The Military Uses of Satellites ................ 34
    2.1.2 The Increasing Military Dependence on Space ... 37
    2.1.3 Cables as an Alternative to Satellite Communications 37
    2.1.4 Summary ........................................ 39
  2.2 KKV's the Ultimate Space Weapon .................... 39
    2.2.1 The Target Visibility Advantage ................. 39
    2.2.2 ASAT Detection .................................. 41
    2.2.3 The Impact Kill Advantage ...................... 42
2.2.4 The Orbital Mechanics Advantage

2.3 Launch Costs: Rockets and Gun Launchers

2.4 Cost Comparison

2.4.1 Gun Launcher Advantages

2.4.2 Destroying Gun Launchers

2.5 Decoys, Anti-Anti-Satellites and Self-Defending Satellites

2.5.1 Decoys in LEO

2.5.2 Decoys in GEO and SSO

2.5.3 Self Defense and Maneuver in GEO or SSO

2.6 Alternative ASATs

2.6.1 Co-Orbital ASATs

2.6.2 GEO Communications Jammer

2.7 Laser ASATs

2.7.1 Ground-Based Laser ASATs

2.8 Nuclear Weapons

2.9 Summary

3 Future Threats and How to Meet Them

3.1 Future U.S. Conflicts

3.1.1 Insurance and Uncertainty

3.2 Threats to the U.S.

3.2.1 Offensive Options

3.2.2 Jamming

3.2.3 Nuclear Weapons in Space

3.2.4 KKV's

3.2.5 Summary

3.3 A Realistic U.S. Military Space Policy: What to Do Now

3.3.1 Hardening Military Satellites Against Nuclear Attack

3.3.2 Hardening Commercial Satellites Against Nuclear Attack

3.3.3 Uplink Jamming
II Detailed Technical and Historical Considerations 117

4 The Physics of Earth Orbit 118

4.1 The Medium of Space 118

4.1.1 Land, Sea, Air, and Space 119

4.1.2 Earth Geography 122

4.2 Earth Orbit 126

4.2.1 Kinetic and Potential Energy 126

4.2.2 Orbital Equations 129

4.2.3 Perturbations in Low Earth Orbit 131

4.2.4 Geosynchronous Orbital Perturbations 135

4.3 Methods of Attack 136

4.3.1 Co-Orbital Assault 137

4.3.2 Pop-Up Assault 148
5 Kinetic Attack

5.1 Vulnerability ......................................................... 154
  5.1.1 Hypervelocity Impacts ........................................... 155
  5.1.2 Non-Catastrophic Collisions .................................... 155
  5.1.3 Catastrophic Collisions ......................................... 157

5.2 Target Shielding ..................................................... 159
  5.2.1 Shielding Requirements ......................................... 159
  5.2.2 Satellite Characteristics ....................................... 160
  5.2.3 ASAT Mass ....................................................... 163
  5.2.4 Shield Masses ................................................... 163
  5.2.5 Attacker Advantages ........................................... 164
  5.2.6 Summary .......................................................... 167

6 Rockets ................................................................. 169

6.1 Ideal Rockets ....................................................... 169
  6.1.1 Specific Impulse ................................................ 171

6.2 Non-Ideal Rockets .................................................. 172
  6.2.1 Staging ......................................................... 173
  6.2.2 Gravity Losses ................................................ 174
  6.2.3 Vertical Height with Gravity Losses ......................... 175

6.3 The Cost of Reaching 200 km ...................................... 176
  6.3.1 Horizontal Acceleration Cost .................................. 178

6.4 Re-Evaluation of the Pop-Up Attack .............................. 181
  6.4.1 Target vs Attacker Cost ....................................... 181
  6.4.2 Target Maneuver ............................................... 182
  6.4.3 Targets in GEO ............................................... 184
  6.4.4 Summary ........................................................ 185

6.5 Rocket Inventory: Launch Costs .................................. 185
  6.5.1 Rocket Survey .................................................. 186
  6.5.2 LEO Cost Base Line .......................................... 194
6.5.3 GTO Cost Estimate ........................................ 194
6.5.4 GEO Cost Estimate ......................................... 195
6.5.5 Summary .................................................... 196

7 Laser ASATs .................................................... 197
  7.1 Space-Based Lasers ......................................... 197
  7.1.1 Laser in LEO ............................................. 198
  7.1.2 Laser in GEO ............................................. 198
  7.1.3 Complicating Factors .................................... 199
  7.2 Ground-Based Lasers ....................................... 201
  7.2.1 Mirrors .................................................. 201
  7.2.2 Atmospheric Absorption and Laser Frequency ........ 203
  7.2.3 Atmospheric Turbulence ................................ 203
  7.2.4 Thermal Blooming ....................................... 206
  7.2.5 Laser Focusing ......................................... 207
  7.2.6 Laser Beam Area ....................................... 208
  7.3 Laser Shields .............................................. 209
  7.3.1 Laser Heat Shields ..................................... 211
  7.3.2 A Limited Duration Heat Shield ....................... 212
  7.4 Alternative Futures for Laser ASATs .................... 215
  7.5 Conclusions .............................................. 219

8 The Global Positioning System ................................ 220
  8.1 The GPS Constellation .................................... 220
  8.2 GPS Accuracy and Selective Availability ............... 222
  8.2.1 The Glonass Satellite Navigation System ............. 223
  8.2.2 Absolute Accuracy Now Available ..................... 224
  8.2.3 Differential GPS ...................................... 225
  8.3 A Military GPS Policy .................................... 226
  8.3.1 Denial of GPS Services to Commercial Users ........ 227
  8.3.2 Inmarsat and Codes via Satellite ..................... 228
8.3.3 Other GPS Users ........................................... 228
8.3.4 The Possibility of Foreign GPS-like Systems .......... 229
8.3.5 Fall-Back Position ........................................ 231
8.4 Summary ....................................................... 232

9 Further Technical Considerations .......................... 233

9.1 Military Satellite Inventory ................................. 233
  9.1.1 Photo Reconnaissance Satellites ................. 236
9.2 Launch Site Locations ..................................... 238
9.3 Detection Requirements for ASAT Attack ............ 241
  9.3.1 LEO targets ............................................ 241
  9.3.2 GEO Targets ........................................... 244
  9.3.3 Existing DSP Coverage ............................ 254
9.4 Decoys ....................................................... 255
  9.4.1 Decoy Mass ............................................ 257
9.5 Space Guns .................................................. 259
  9.5.1 Launch Calculation .................................. 262
  9.5.2 Space Gun Infrastructure ....................... 263
9.6 Nuclear Weapons ........................................... 266
  9.6.1 Nuclear Weapon Cost and Weight ............... 269
  9.6.2 Political Implications ............................ 270
9.7 Communications Jamming ................................. 271
9.8 System Development Timelines ............................ 275
  9.8.1 GEO Boosters ........................................ 277
  9.8.2 Large Military Satellites ....................... 278
  9.8.3 Micro Communications Satellite Systems ...... 278
  9.8.4 ASATs ............................................... 279
  9.8.5 Nuclear ASATs ...................................... 280

10 The Politics of Space Missions .......................... 282

10.1 Organizational Theory ................................... 283
10.2 Rocket Wars: The Struggle for Access .................................. 287
  10.2.1 Early Rocket Development: The Early 1940's .................. 288
  10.2.2 Decline in Missile R&D: The Late 1940's .................... 294
  10.2.3 Missile Development: the 1950's ............................... 298
  10.2.4 Changing of Opponents: The Army and Navy Out, NASA In 313
  10.2.5 Summary of Booster Development ............................ 317

10.3 Manned Missions: NASA Defeats the Air Force .................... 321
  10.3.1 The Military Utility of Manned Missions .................... 322
  10.3.2 NASA Versus the USAF: Early Struggles .................... 323
  10.3.3 NASA Takes Off, USAF Is Canceled .......................... 327
  10.3.4 Tight Budgets and Forced Accommodation .................. 329
  10.3.5 Summary of Manned Missions ................................ 332

10.4 Reconnaissance Satellite Development ............................ 333
  10.4.1 Early Developments in Overhead Reconnaissance and the "Gaps"334
  10.4.2 Air Force Motivations ....................................... 335
  10.4.3 Alternative Technologies ................................... 335
  10.4.4 Corona and SAMOS .......................................... 336
  10.4.5 Attempts at Centralization .................................. 337
  10.4.6 The Competition Continues .................................. 339
  10.4.7 Reconnaissance Satellite Summary .......................... 342

10.5 Communications Satellite History ................................ 344

10.6 ASAT Development .................................................... 347
  10.6.1 ASAT Summary ................................................ 350

10.7 The Current Status of Military Space Missions .................. 351

10.8 Historical Lessons .................................................. 355

10.9 Policy Recommendations ............................................ 360

A Soviet ASAT Kill Radius Calculation ................................ 365

B Brilliant Pebbles Calculation ........................................ 367
C  Orbital Simulation Code  370

D  Space Gun Launch Simulation Code  372
List of Figures

3-1 Policy Timeline, Threat Levels One and Two .............. 112
3-2 Policy Timeline, Threat Levels Three, Four, and Five ............. 113

4-1 Kinetic and Potential Energies of Earth Orbits .............. 128
4-2 Attempt to Intercept in 90 Degrees ...................... 144

6-1 Launch Cost Rates into LEO as a Function of Payload ........ 189
6-2 Launch Cost Rates into GTO as a Function of Payload ........ 191
6-3 Launch Cost Rates into GEO as a Function of Payload ........ 192

9-1 Infra-Red Emission Diagrams ......................... 246
9-2 Kill Radius of a 1 Megaton Nuclear Detonation .............. 267
## List of Tables

2.1 Costs of Targets and ASATs ................................................. 50
2.2 Ground-Based Laser ASAT Alternative Future Requirements ........ 60

4.1 Pop-up Mission ΔV Requirements ......................................... 151
4.2 Orbital Mission ΔV Requirements ......................................... 151
4.3 Comparison of ΔV Requirements for Pop-Up Attacker vs Target Satellite 152

5.1 γ’s for Non-Catastrophic Collision, Γc’s for Catastrophic Collision ... 156
5.2 Relative Shield Thickness Requirement ................................... 161
5.3 Shield Masses for Satellite Radii vs Impact Velocity ................... 164
5.4 Attacker Advantages for an Unshielded Target ........................... 165
5.5 Attacker Advantages for an Shielded Target ............................. 165

6.1 Approximate Orbital Lifetimes .............................................. 174
6.2 Payload Percentages for Various Missions ............................... 179
6.3 Rocket Size Advantages for Pop-Up Attacker vs Target Satellite ...... 182
6.4 Ascent Times from the Surface of the Earth ............................. 183
6.5 Booster Costs and Performance ........................................... 190
6.6 Booster Payload Percentages .............................................. 193

7.1 Beam Areas for 4m and 10m Diameter Mirrors ........................... 208
7.2 Ground-Based Laser ASAT Alternative Future Requirements .......... 216

9.1 Deployment of U.S. Military Satellites .................................. 234
9.2 Deployment of Soviet Military Satellites, 1987 .......................... 235
9.3 Operational Launch Sites ............................. 239
9.4 Communications Data Rates ............................. 274
9.5 Space System Development Times ......................... 276

10.1 Defense Obligational Program for Missile Systems Fiscal Years 1946-60
   (in millions of dollars) ............................. 296
0.1 Glossary

This is a list of terms and acronyms used throughout the dissertation:

- Anti-Satellite system (ASAT). An interceptor designed to destroy satellites in orbit.

- Anti-Anti-Satellite system (AASAT). This is an interceptor designed to destroy an ASAT before it reaches its target.

- Ballistic Missile Defense (BMD). At minimum, it consists of a sensing/trackins system to detect incoming missile warheads and an interceptor system designed to destroy incoming ballistic missile warheads. To be sucessful, a BMD system will also probably have to deal with nuclear weapons effects, jamming, and decoys. The Star Wars program is a BMD program. Because the closing velocities are very high, BMD interceptors make good ASATs as well. Ground based BMD interceptor missiles currently under development are limited to low altitudes and so may not be true ASATs, but they contain the most technologically demanding component of an ASAT, the KKV interceptor.

- Defense Support Program (DSP). This is a constellation of three U.S. early warning satellites. They use SWIR detectors to track all missile launches up to 81 degrees north and south latitude. Once the missile rocket burns out, DSP cannot see these missiles, but it can predict the missile trajectory based on the flight path during boost. DSP satellites are also capable of detecting aircraft using after burners.

- Defense Satellite Communications System (DSCS). This is a constellation of GEO communications satellites intended for U.S. military communications. Currently x are in orbit. Eventually, they are supposed to be replaced by the Milstar system.

- Field Of View (FOV). This refers to the area of the Earth's surface visible to a satellite at a particular moment in a particular orbit. It can also refer to the
volume of space visible to a ground-based radar which is limited by the Earth's surface. It can also refer to the area visible through a telescope.

- Geo-Synchronous Orbit (GEO). This circular orbit corresponds to the orbital period of the Earth's rotation (slightly more than 24 hours). When the orbit is inclined at an angle of zero degrees and runs from west to east, the orbit becomes geo-stationary. This places the satellite in a fixed position relative to the Earth's surface while providing a large viewing area of the Earth. For these reasons, almost all communication satellites are in geostationary orbits. The word geo-synchronous has become synonymous with geo-stationary. In this dissertation we will use "GEO" and "geo-synchronous" to refer to the geo-stationary orbit.

- Geo-Synchronous Transfer Orbit (GTO). This is an elliptical orbit that transfers between LEO and GEO with a minimum energy requirement. The orbit perigee is at LEO, while its apogee (180 degrees later) is at GEO altitude. The time it takes to transition from one altitude to the other is 5.15 hours.

- Global Positioning System (GPS). This is a soon to be completed constellation of 21 U.S. navigation satellites in SSO. By emitting precise time and orbit information they allow receivers on the ground to determine their position and velocity in three dimensions.

- GLONASS. A Soviet constellation of navigation satellites in SSO. By emitting precise time and orbit information they allow receivers on the ground to determine their position and velocity in three dimensions.

- Infra-Red (IR). This is a band of the electromagnetic spectrum next to the visible light band beginning at the 1 µm wavelength and continuing up through longer wavelengths. All objects radiate in the IR band based on their surface temperature and emmissivity. A perfect black body has an emmissivity of 100%, a perfect reflecting body has an emmissivity of zero. Object radiate over a range of IR frequencies, but the peak wavelength varies with temperature. The higher
the surface temperature, the shorter the peak wavelength, this is why very hot objects appear to glow, their IR radiation is moving down into the visible band. Thus longer wavelength portion of the IR band is called the Long Wave Infra Red (LWIR).

- Kinetic Kill Vehicle (KKV). This is the newest generation of hit-to-kill ASAT under development by the U.S.. It is capable of striking object with a closing velocity on the order of 10 km/sec. Tested KKV's weigh tens of kilograms, but new designs under development are expected to weigh less than 5 kg. This dissertation concludes that this is the most effective space weapon currently available.

- Long Wave Infra Red (LWIR). This is the portion of the IR band in which cooler objects radiate. Because so many objects are in this temperature range, it is difficult to pick out an object with a LWIR sensor, except against the very cold background of space. Even then, if the Earth’s atmosphere is in between the object and the sensor, the air’s LWIR radiation can drown out the fainter object’s LWIR radiation.

- Low Earth Orbit (LEO). The orbit that is closest to the Earth while remaining above the Earth’s atmosphere. All satellites that use LEO exist in a belt between 200 km and 1,800 km altitude. Below 200 km, orbits decay very quickly because of atmospheric drag.

- Mega Bits Per Second (Mbps). This is a measure of data flow. One Mbps is one million bits of information transmitted per second. A bit is the smallest piece of information indicating a yes or no condition.

- Miniature Homing Vehicle (MHV). An early hit-to-kill ASAT system which is launched from an F-15 fighter aircraft. It is a KKV, but is much heavier than KKV’s currently under development in the U.S. This system can impact a satellite while closing with its target at a speed on the order of 10 km/sec. This system weighs 25 kg. Several are currently in storage.
- On Orbit Satellite Cost. This is the cost of building the satellite, plus the cost of launching it into orbit. It is interesting to note that in the commercial world, the cost of these two factors, construction and launch, are almost always within a factor of two of each other. This a result of two factors: first, given a particular function, lighter satellites are more expensive to build than heavier ones; and second, boosters which boost heavier payloads cost more than booster which launch lighter payloads. Thus, it’s not worth spending so much on a light satellite that the satellite costs outweigh the savings on the booster costs. Nor is it worth spending so much on a powerful booster that the booster costs outweigh the savings on building a heavier satellite.

- Semi-Synchronous Orbit (SSO). This circular orbit corresponds to half the orbital period of the Earth’s rotation (slightly more than 12 hours). It is used by the GPS and GLONASS navigation systems.

- Super-Synchronous Orbit. This refers to all orbits that are higher in altitude than GEO. The super-synchronous orbits with zero degrees of inclination can be used as a place to store or hide on-orbit spare satellites. It is also used by the U.S. Vela nuclear detonation detection satellites. It is also good place to dump used GEO satellites because it is big and easy to get to from GEO.

- Upper Low Earth Orbit (ULEO). Most LEO satellites range in altitude from 200 km to 1,800 km. ULEO is this upper bound. This limit is not a fixed one, however there is little that orbits above this altitude have to offer (except for Molnya, SSO, and GEO orbits).
Part I

A U.S. Military Space Policy
Chapter 1

Executive Summary

Today, satellites are performing an ever increasing range of military functions. They act as force multipliers, increasing the effectiveness of forces on Earth. Satellites provide reconnaissance, signals intelligence, communication, and navigation on a global scale. As U.S. military satellites become more integrated into U.S. military operations, military operations without these satellites will become increasing difficult.

Satellites have become valuable military targets. This means that in the future the U.S. may need to defend its satellites from enemy attack. The U.S. may also require means of neutralizing hostile satellites.

This dissertation is intended to provide a guide to the kinds of space systems, both offensive and defensive, the U.S. should be building today and what kinds of systems might be needed in the future. My intended audience is the civilian decision maker. This dissertation has two purposes: to illuminate the nature of war in space and to construct a military space policy for the United States.

1.1 Designing a U.S. Military Space Policy

This section summarizes my argument for the space policy I propose. Here I present my conclusions about the future military space policy for the U.S.

So much uncertainty exists about future military threats to the U.S., that these policy decisions must be based on certain assumptions. In the Chapter 3, I examine
the range of threats that hostile nations could pose. I find that enemy technological
capability determines the threat to U.S. space assets. Below, I define five threat levels
based on enemy technological capability. I have produced a set of recommendations
for each of these five projected threat levels: nuclear and low powered laser attacks,
limited Soviet-type Anti-Satellite (ASAT) attacks, limited Kinetic Kill Vehicle (KKV)
ASAT attacks, unlimited KKV ASAT attacks, and ground-based laser ASAT attack.

I begin with a set of recommendations designed to counter current threats (Threat
Level One). These measures can be increased as the threat increases, at increased cost.
Unfortunately, additional measures do not always build upon previous measures. For
example, decoys are an effective way of defending large Geosynchronous Orbit (GEO)
communication satellites from limited numbers of KKV ASATs. But if faced with
thousands of KKV ASATs, the appropriate response is to abandon large satellites in
GEO and to set up a network of micro-satellites that can compete with the KKV
ASATs effectively in terms of cost and replaceability.

This latter measure is extreme. We use large satellites because they are more
cost effective. Design times and orbital lifetimes for these systems are measured in
decades. The recommendation is to continue with these designs and to buy decoys if
the threat is small, but to abandon large satellites and to build micro-satellites if the
threat is large. The problem is that some decisions must be made now, before the
threat is known. Further, the costs are also being paid now. Do we invest billions in
the Milstar communications satellite constellation on the assumption that the threat
will be low? Or do we pay more for a micro-satellite constellation on the assumption
that the threat will be high? If we build Milstar and the threat is large, we’ve wasted
billions of dollars and we’re left without a communications system. If we build micro-
satellites and the threat is small, again we’ve wasted billions of dollars on a system
that is cost-ineffective.

Fortunately, it also takes a long time to design and build ASAT systems. More
precisely, it has taken the U.S. and U.S.S.R. a long time to develop and test their
ASAT systems. This holds out a ray of hope. Should a nation hostile to the U.S.
embark on a KKV ASAT development program, it could be ten years before such
a system is operational. Even if the development phase is concealed from the U.S., the ASAT development record indicates that the U.S. would still have three years warning from the first successful test to initial deployment. Thus, I argue that radical expensive measures are not required now because we will have as much as ten years warning of an ASAT campaign. Even then, war with an ASAT capable nation is not necessarily going to happen the moment its ASAT system becomes operational. Thus, the U.S. will probably have many years in which to react to an emerging ASAT threat.

1.1.1 Intentions and Capabilities

Currently the U.S. is at peace and most nations of the World do not have an ASAT program. If a nation already has a conventional ASAT, warning time may be dramatically reduced. This is because national intentions can change much faster than technological capability. The two nations that currently have or have had such programs are the U.S.S.R. and Israel.

The military space program inherited by Russia from the U.S.S.R. has a tested co-orbital ASAT system. This system could be brought back on line very quickly and so represents a possible near term threat. It might also be sold by Russia to another power. It is for this reason that one of the threats anticipated below is a Soviet-type co-orbital ASAT. Russian intentions towards the U.S. have recently changed for the better. But as the attempted coup in Moscow demonstrated, Russian intentions could quickly change. Thus, I treat Russia as a possibly hostile nation and base our defenses on its capabilities.

Israel, with U.S. help, has already embarked on a project that could give it a KKV ASAT capability. In fact, this program is a ballistic missile defense (BMD) program, but even a poor anti-ballistic missile system can make a very good ASAT system. As long as Israel remains friendly or neutral towards the U.S., which seems very likely, then we have little to fear.

One concern is that Israel might sell its BMD technology to other nations that might be hostile to the U.S. The recent Gulf War has demonstrated the potential of
ballistic missiles for attacking civilian populations. Many nations now want to buy a BMD system.

Extreme caution would dictate spending the money to avoid the risk that the Israeli system might be used on U.S. satellites. But then we are building systems to deal with other systems we are paying our ally to develop. This is simply paranoid, not to mention extremely wasteful. Instead, we should assume that Israel’s long-standing special relationship with the U.S. will continue and that the Israeli system will not be used against the U.S. Further, while Israel has much to gain from having a BMD system, it has much to lose if its neighbors acquire BMD systems of their own. I feel that we can trust the Israelis to be concerned about BMD/ASAT proliferation.

A space policy must recognize that the U.S. has a limited budget. Military risks must be traded off against other, perhaps more pressing risks or needs, such as environmental destruction or economic competitiveness or education. My approach in this dissertation is to advocate low-cost measures that increase the survivability of U.S. space assets and to postpone any high-cost measures until necessary. The low-cost measures I advocate are an insurance policy against the possibility of a future war in space. Today this seems a remote possibility, but insurance is designed to provide a hedge against distant, yet dangerous, possibilities.

Future high-cost measures are based on the potential future capabilities of hostile nations. It is up to the implementor of this policy to judge the intentions of any nation that may initiate development of ASAT capabilities in the future. Russia and Israel were fairly simple cases, but future cases may be more ambiguous. Future decision makers will have to balance the costs of defending satellites against the risk of war with an ASAT-capable nation. My space policy cannot make that decision for them, but it can lay out the necessary measures that would be needed to defend U.S. satellites in particular circumstances.

1.1.2 The Nature of Space Warfare

Before detailing these policy recommendations, here is a quick summary of what does and does not work in space.
Satellites in Earth orbit are very visible. Those in Low Earth Orbit (LEO, 200 to 1,800 km above the surface of the Earth) can be seen with radars. Satellites in Semi-Synchronous Orbit (SSO, 20,183 km above the surface of the Earth) and Geosynchronous Orbit (GEO, 35,785 km above the surface of the Earth) can be detected with ground-based telescopes, but there are ways for satellites to avoid ground-based detection. For higher orbital altitudes (SSO and GEO), space-based Long Wave Infra-Red (LWIR) detectors are required to see every satellite.

Nuclear ASATs have a large lethal radius against unshielded satellites, so the U.S. should shield all its satellites against long range effects. Against shielded satellites, nuclear weapons are still effective ASATs, but they are unlikely to be used because of the political problems they produce. Under very specific conditions, I can imagine a nuclear power using small numbers of nuclear ASATs against U.S. satellites in LEO, but this is unlikely. All other conditions seem to prohibit the use of nuclear weapons for ASAT missions, see Section 3.2.3 p. 75 for more details.

Laser ASATs offer the possibility of destroying satellites at a distance with multi-shot weapons. However, space-based lasers are too vulnerable to direct-impact conventional ASATs (Kinetic Kill Vehicles or KKV) to be effective. Ground-based lasers would be more secure, but it is very uncertain whether or not such a system can be built. Given the current U.S. lead in KKV technology, ground-based lasers offer little to the U.S. that KKV do not already provide. Given the increasing U.S. dependence on its military satellites, ground-based laser ASATs are a technology that the U.S. should not encourage. Thus, laser ASATs provide little benefits and much potential harm to the U.S. Fortunately, there are currently many technological obstacles preventing their deployment.

KKVs are the best method for destroying satellites. Orbital mechanics give small KKV the ability to destroy large satellites while denying the targets any hope of shielding against them. In LEO, decoys against KKV are useless. At higher altitudes, decoys are more effective against KKV, but many decoys have to be used and the attacker has several counter-counter-measures available to him.

In general, U.S. satellites in LEO are more vulnerable than those in SSO or GEO.
The technologies required to attack satellites in LEO with either nuclear or conventional ASATs are less complex than those required to attack satellites in SSO or GEO. Thus, in the face of limited ASAT threats, the U.S. can rely on its communications satellites in GEO and its navigation satellites in SSO. However, the U.S. can also expect to quickly lose its reconnaissance satellites in LEO if a war breaks out.

If the U.S. is faced with an opponent with large numbers of KKVs, the only viable defense is to abandon the small constellations of large satellites in high orbits and to deploy large constellations of very small satellites in LEO. Navigation and communication missions can be performed with these "micro-satellite" systems, the reconnaissance mission cannot. In wartime, the U.S. will have to depend on terrestrial reconnaissance systems such as aircraft. A gun launcher could halve the cost of launching micro-satellites.

1.1.3 Five Threat Levels

I have categorized the future military space environment into five threat levels. For each threat level, I present a set of recommendations. After each recommendation, the supporting chapter and section numbers are listed in braces. Overall, I advocate adopting the low-cost (less than 5% added system cost) counter measures now, while deferring all other measures until warning of a military space threat is received. The one exception is anti-jamming measures, which substantially increase communications satellite costs. The five threats and counter measures follow.

- Threat Level One: the lowest level threat based on the current world. The U.S. sees few military threats while Russia continues to decline as a significant military power. U.S. space assets will only be threatened by a small number of nuclear detonations in space, ground-based jamming, or low powered laser attack.

Defensive Measures:

1. Continue to build hardness against long distance nuclear effects and resistance to low power laser attack into all military satellites. Cost: 3%
increase in satellite costs. [Sections 3.3.1 p. 86, 3.2.3 p. 76, 9.6 p. 266]

2. Encourage commercial carriers of defense communications traffic to also harden their satellites. This encouragement could come in the form of subsidies or preferential purchases, as well as U.S. voting power within the Intelsat and Inmarsat corporations. Unfortunately, commercial carriers will probably resist U.S. efforts. Cost: 3% increase in commercial communications satellite costs, passed on to users. [Sections 3.3.2 p. 87, 3.2.3 p. 76, 9.6 p. 266]

3. Continue to design anti-jamming features into U.S. military satellite uplinks. Cost: roughly a factor of 17 increase in communications satellite cost. [Sections 3.3.3 p. 89, 3.2.2 p. 75, 9.7 p. 271]

4. Add decoys and impact sensors to LEO satellites. Cost: minimal compared to cost of satellites. [Sections 3.3.4 p. 90, 9.4 p. 255]

5. Make precision GPS signals available to civilian users worldwide but warn users that the U.S. retains the right to encode all GPS signals during wartime. Cost: disruption of civilian navigation during a crisis. [Section 3.3.5 p. 92, Chapter 8, p. 220]

6. Support the Motorola Corporation's decentralized communications satellite project with FCC approval, diplomatic support for acceptance in other nations, and long term communications purchases. [Sections 3.3.6 p. 92, 3.4.3 p. 109]

7. Continue research on gas gun space launchers, electromagnetic gun launchers, and chemical gun launchers to determine their full-scale development costs. Cost: roughly $4 million/year. [Sections 3.3.7 p. 93, 2.3 p. 44, 9.5 p. 259]

Offensive Measures:

1. Continue to store and maintain existing miniature homing vehicle ASATs as an offensive option. Replace them with the miniaturized version cur-
rently under development when it becomes available. Do not fund further U.S. KKV ASAT development. Of course, this recommendation will be effectively ignored if the Star Wars program continues KKV research since most kinetic Star Wars systems can also be used as ASATs. Cost: $60,000 per year for storage.¹ [Section 3.2.1 p. 73]

2. Halt research into high powered ground-based and space-based laser ASATs. Again, this recommendation will be effectively ignored if the Star Wars directed energy program continues. Cost: savings from the Star Wars program, unknown amount. [Section 2.7 p. 59, Chapter 7 p. 197]

3. Remain aware that old communications satellites in GEO might be used to jam other communications satellites. [Section 2.6.2 p. 58]

And in the area of the space environment management: [Section 3.3.11 p. 97]

1. Work towards an international agreement to minimize orbital debris in higher orbits. Cost: loss of 1 to 2 months of lifetime for each satellite.

2. Begin research into an orbital janitor system to remove discarded satellites from the heavily used GEO by moving the spent satellites into super-synchronous orbit.

3. Work to get Russia to stop launching nuclear reactors to power its ocean reconnaissance satellites (this may already have happened).

- Threat Level Two: a low level threat based on a re-vitalized Russian military. In addition to the threats mentioned above, the co-orbital ASAT system, originally developed by the Soviet Union, is rebuilt and deployed by Russia. Once the LEO ASAT became operational, Russia might undertake development and testing of a GEO version of its co-orbital ASAT. [Section 3.4.1 p. 101]

1. If we have followed recommendation #4 under defensive measures in Threat Level One above, we should have already added decoys and impact sensors.

¹Finnegan, Philip and Vincent Kiernan “After $1.8 Billion, Pentagon Kills ASAT Effort” Defense News, January 7th, 1990, pp. 4 & 31. The storage costs are $5,000 per month or $60,000 per year.
to all LEO satellites. The DSP network should provide sufficient warning of an attack to allow decoys time to deploy. Cost: minimal compared to satellite cost. [Sections 9.3.3 p. 254]

2. Invest in decoys and impact sensors for satellites in SSO and GEO as a hedge against the possibility of an enemy initiating development of a co-orbital GEO ASAT. Existing DSP early warning satellites can probably provide ASAT attack warning for SSO and GEO satellites. There would be gaps in coverage, however, any Soviet-style ASAT attempting to attack without being detected would require too large and too costly a rocket for such a mission.

• Threat Level Three: a more sophisticated threat consisting of initial development or testing of a KKV ASAT. [Section 3.4.2 p. 103]

1. Accept that LEO reconnaissance and weather satellites will be destroyed in a war with a nation equipped with KKV's. These satellites provide useful functions in peacetime, so their continued use will be warranted. As wartime backups, we should use weather satellites in GEO. Cost: none, these backups already exist for other reasons. [Chapters 4 p. 118, and 5 p. 154]

2. It will probably not be possible to build small reconnaissance satellites capable of producing the detailed images we receive today. As a wartime backup for the reconnaissance satellites, continue to maintain a small number of reconnaissance aircraft (reconnaissance versions of the F-4 and F-16, AWACs, JSTARS, and TR-1s). Cost: aircraft already exist for other reasons.

3. If a hostile nation with GEO boosters begins development of KKV's or a hostile nation with KKV's begins development of a GEO booster, do two things:

   – Build a 2 GEO satellite LWIR space surveillance system. Cost: roughly $700 million. [Section 9.3 p. 241]
- Place large numbers of decoys (on the order of 100 per satellite) and impact sensors on all SSO and GEO satellites as a hedge against a higher altitude version being developed. Cost: 5 to 10 percent of on-orbit satellite cost.

- Threat Level Four: a high level threat consisting of thousands of KKV ASATs capable of reaching GEO altitudes. [Section 3.4.3 p. 107]
  1. Begin research and development of very light, cheap communications and navigation satellites designed to be placed into LEO in large numbers. Cost: unknown, but if we have followed recommendation #6 under defensive measures for Threat Level One above, Morotola's Iridium project will provide a working prototype.
  2. If research into gun launchers provides a system as low in cost as predicted, build it. Cost: perhaps $7 billion.

- Threat Level Five: the highest level threat consisting of ground-based laser ASATs using adaptive optics, thermal blooming compensation, 2-8 MW lasers, and 4m mirrors. [Section 3.4.4 p. 111]
  1. Abandon satellites in LEO and shield all satellites in SSO and GEO.
  2. If the threat seems likely to increase to 10's of MW using 10m mirrors, military satellites become indefensible. Abandon military space satellites in favor of terrestrial alternatives.

1.1.4 Current U.S. Offensive Capabilities

This military space policy focuses primarily on defensive measures. This is because the U.S. tends to fight it wars far from home, and is becoming more dependent on its military space assets every day (see Sections 2.1 and 3.1). Of less concern is the U.S. need to attack other nations' military space assets. Few nations other than the former Soviet Union have more than a handful of military satellites. Only a re-vitalized and hostile Russia could present the U.S. with a military satellite target set that would
represent any challenge. Even then, the U.S. already has the tools to build ASATs to attack satellites at any altitude.

The U.S. already has a tested KKV ASAT system in storage, the Miniature Homing Vehicle (MHV). Star Wars researchers are producing a second generation miniaturized KKV system. Thus, using the five threat categories listed above, the U.S. already qualifies as a level three threat (limited KKV ASAT) to any other nation. The U.S. is quickly moving toward becoming a level four threat (unlimited KKV ASAT). U.S. ASATs are currently limited to LEO, but the U.S. has boosters capable of reaching GEO and equipment to track targets up to GEO altitude. Thus, we already have all the components needed to build a GEO-capable KKV ASAT, it is simply a matter of putting the pieces together and testing them. Finally, the U.S. is probably the only nation seriously researching high powered lasers, which could present a level five threat to other nations.

The U.S. already has an impressive offensive capability with few targets to attack. It will increase this capability even more as a side effect of the Star Wars program. U.S. offensive capability is already larger than is currently warranted and is growing larger. Thus, little needs to be done to bolster the offensive needs of the U.S. Even if all research were halted today, the existing capabilities and prototypes are sufficient to react to any emerging target set. The U.S. already has enough technology and equipment sitting in storage to deal with any buildup of enemy military satellites. Offensively, the U.S. is already as strong, if not stronger, than it needs to be.

1.1.5 Biases and Preferences of the U.S. Military Services

In this dissertation I describe the histories of the U.S. military services in space (see Chapter 10) in order to determine the biases and preferences present in existing military space organizations. My intent is to provide a guide for the space policy implementor.

The Air Force is the dominant service in space. It will be inclined to welcome and implement the recommendations which involve improving existing systems such as adding decoys, nuclear hardness, and anti-jamming features to existing satellites
system. The Air Force will also seek to develop manned systems, but should be prevented from doing so. There is not justification for military manned space systems.

If it becomes necessary to implement new space systems such as gun launchers, micro-satellites, or KKV ASAT deployments, existing space institutions in the Air Force are likely to be hostile and drag their feet. In order to implement these policies, the Army and the Navy should be invited, even pushed,\(^2\) into developing systems of their own, in competition with each other and the Air Force. Unless existing organizations within a service have incentives to pursue a new space project assigned to that service, it may be necessary to create a sub-organization within the service with a separate channel of funding. Also, without senior officers to staff the new sub-organization, the long term survival of the new sub-organization is in danger.

The history of the services in space indicates that although competition produces multiple programs, it also motivates outside organizations to be innovative in developing systems. Established organizations, which would not be inclined to explore new ideas, then feel threatened and begin to apply their resources in new ways. In other words, competition produces innovations that might be shelved if the task were simply given to the established organization.\(^3\)

### 1.1.6 Dissertation Road Map

This space policy is a result of my investigation of space as an arena of military operations. My investigation covers three areas.

The first area is the nature of space warfare itself. Chapter 2 focuses on this topic, introducing themes that are treated in more technical detail in chapters 4 through 9. Objects orbiting the Earth are subject to a distinct set of movement dynamics,

---

\(^2\)Because service cooperation is very prevalent today, it may be necessary to encourage the Army or the Navy to initiate new space projects. Some civilian initiative (and of course money) may be required.

\(^3\)A good example of this is the space launcher. Both NASA and the Air Force are unlikely to pursue this option with enthusiasm. This is because they both have large, established rocket launch organizations which are not inclined to undermine their technology and expertise with a radical solution. Further, a gun launcher will not be able to launch manned missions, something both NASA and the Air Force like to do. Thus, if a successful gun launcher is to be developed, it should be given to an outside organization (with no established rocket launch facilities) to develop.
just as flying aircraft and floating ships are subject to distinct movement dynamics. These dynamics confer advantages and disadvantages to attackers and defenders of satellites. What are the physical laws of movement in space? What types of anti-satellites (ASAT's) will be effective? What military systems exist and what are their capabilities? What systems will become vulnerable? What countermeasures will be effective? My dissertation examines the space environment from a military perspective. In effect, I wish to establish a field manual for this new medium.

The second area of investigation is the type of opponent the U.S. is likely to face in a future war and what the U.S. response should be to that threat. Threats range from third world nations with no space assets to nuclear powers with both military satellites and anti-satellite systems (ASATs). Some threats are more probable than others. Some technologies are more widespread than others. This dissertation intends to develop a military space policy that defines appropriate responses to each of these threats. Chapter 3 is devoted to detailed discussion of policy recommendations.

The third area of investigation is the ambitions and inclinations of the Army, the Air Force, and the Navy toward space roles and missions. In Chapter 10, I review the history of the military services to determine how their prior experiences may have biased their views of space missions. The chapter attempts to divine what missions the services are likely to push for and resist. It is a road map of military preferences intended for the civilian decision maker.

An area that is not covered in this dissertation is strategic defense. While nuclear war is certainly a military operation, it is beyond the scope of my work. I am focusing on the contribution of space technology to "conventional" military operations. This does not mean that I ignore nuclear operations completely. In several areas, the two worlds overlap: nuclear weapons make good ASATs; use of nuclear ASATs or destruction of early warning satellites would represent a serious escalation of a conventional conflict; and almost any strategic defense system will, by definition, have an ASAT capability.

In the next chapter I examine the physical realities of war in space.
Chapter 2

The Nature of Space Warfare

In this chapter I examine space warfare technology, to understand how space systems will work, both on offense and on defense. I will demonstrate that space warfare is currently offense dominant. However, if the defender invests in micro-satellites that balance can be shifted to a more equal footing, perhaps slightly in favor of the defender.

I begin this chapter with a discussion of the increasing U.S. military dependance on satellites. Next, I explain why kinetic kill vehicles (KKV's) are so effective in space. After that, I will cost both satellites and potential ASATs to characterize the current offensive dominance in space and how it can be reduced. Then, I move on to discuss the effects of using decoys and the problems with anti-anti-satellites (AASATs). Next, I discuss alternative ASAT technologies that might be effective if KKV's are not available. Finally, I examine offensive technologies that are not likely to be effective: laser ASATs and nuclear weapons.

2.1 The Military Importance of Space

During our century, we have learned to move in two new environments: air and space. Just as ships and railroads expanded water and land transport, airplanes and rockets have opened up air and space as new media in which to travel, to haul cargo, and to transmit information. And wherever man and his machines have gone, the potential
for war has always followed.

Until recently, space has been an unassailable ‘high ground’ from which one’s satellites could view the battlefield, providing valuable information for reconnaissance, communication, and navigation. But just as fighters and anti-aircraft guns followed the reconnaissance planes of World War I, now offensive space weaponry is being created to attack satellites in space.

Anti-satellite weaponry is being developed because satellites are becoming increasingly important military assets. Satellites provide information to commanders on the ground: what the weather will be, where their forces are, and where their opponent’s forces are. Satellites can also locate radars and intercept enemy radio transmissions. Much of these data have historically been provided by other means. But satellites have produced timely information of an unprecedented quality and quantity.

2.1.1 The Military Uses of Satellites

The U.S. military is still learning to use this new source of information. During the recent Gulf War, many satellite systems (communication, reconnaissance, and navigation) were used to support military operations for the first time.

Satellite communication is the space function that is most integrated into military operations. Global communications during the Gulf War were in great demand. As one Air Force officer put it: “There was not enough communication satellite capability for everyone who wanted to use it.”¹ At its peak, 85% of all intra-theater communications and 100% of all inter-theater communications in the Gulf War went via satellite.²

Reconnaissance was provided by five to six KH-11 optical imaging satellites. Also used was a radar imaging Lacrosse satellite, which can locate tanks through cloud cover. Missile launch detection satellites, designed to detect ICBM and SLBM

launches, were used to detect Scud launches. All of this data was relayed in real
time via Tracking Data and Relay Satellite System (TDRSS) satellites to the U.S. for
analysis.\textsuperscript{3}

Navigation by satellite was available for the first time during Desert Shield and
Desert Storm. Ground units in a large featureless desert knew exactly where they were
thanks to the Global Positioning System (GPS). The Defense Department ordered
thousands of receivers for the operation. In the U.S., civilians bought commercially
available GPS receivers and mailed them to relatives stationed in the Gulf so they
wouldn’t get lost.\textsuperscript{4} Units coordinating close air support found GPS particularly useful:

Everyone’s favorite new item was the Global Positioning System (GPS)
which allowed accurate navigation and forward air control in a country
nearly devoid of topographical features. It saved people from getting lost
in the desert and bumping unexpectedly into the foe. Moreover, it was
used to accurately locate cleared areas through the extensive Iraqi mine
fields.\textsuperscript{5}

The Navy’s Stand-off Land Attack Missile (SLAM) used GPS to correct its inertial
guidance system. Artillery crews used GPS to determine their location. Tanks broad-
cast their GPS computed position to each other to prevent friendly fire casualties.\textsuperscript{6}
Paths through mine fields were defined using GPS.\textsuperscript{7}

Future military applications of GPS are likely to be as dramatic. Naval ships
engaged in mine sweeping can use GPS to solve the “grid lock” problem. Once a
minesweeper had located an enemy mine, ships and submarines need to be given the
mine’s location. This means they must know their position relative to each other

\textsuperscript{3}Covault, Craig. “Recon Satellites Lead Allied Intelligence Effort,” \textit{Aviation Week \& Space

\textsuperscript{4}Units also purchased their own GPS receivers before being sent overseas. See Nordevall, Bruce
“Imagination Only Limit to Military Commercial Applications for GPS” \textit{Aviation Week \& Space
Technology} October 14th, 1991, pp. 60-64.

\textsuperscript{5}“U.S. Forces Praise Performance of GPS But Suggest Improvements,” \textit{Aviation Week \& Space
Technology}, April 22nd, 1991, p. 75.


\textsuperscript{7}Cannan, James W. “A Watershed in Space” \textit{Air Force Magazine} August 1991, p. 35.
(where they are on the map grid) to make the best use of this data. Errors in relative position increase uncertainty about the mine’s location. GPS solves this problem.

GPS is also expected to enhance artillery pointing accuracy to one milliradian. Current artillery fire control systems have pointing accuracies of 300 milliradians. The Air Force is considering installing GPS receivers on precision guided munitions to provide navigation information in the initial part of its flight (just after being dropped or launched).

GPS will replace existing cruise missile navigation. Currently, cruise missiles use an on board radar to examine terrain features at certain way-points along its flight path. It compares the radar image with a stored computer image to determine where it is. A GPS receiver aboard the missile eliminates the need for the radar and the need to fly over suitable patches of pre-recorded terrain. This could increase missile range by allowing the missile to fly its entire mission over terrain unsuitable for radar guidance. This can also reduce radar emissions, making the missile harder to detect. The next generation of air-delivered stand off munitions are expected to incorporate GPS to increase accuracy to 3 meters. The Navy is planning to delete the radar guidance system from all the cruise missiles it produces in the future. Instead they will use GPS navigation.

In addition, GPS is beginning to become important in space systems. GPS receivers can be used by satellites in low Earth orbit to determine their position. For example, the Pegasus launch system is adopting GPS for navigation purposes. New launchers are also incorporating GPS into their design. Navigation aboard the

---

12Fulghum, David A. "USAF to Increase Bomber’ Precision, Procure Powered Radar Decoys" Aviation Week & Space Technology February 17th, 1992, p. 60.
15Kolcum, Edward H. "Delta Clipper Partners Set Goal For Single-Stage-to-Orbit Vehicle" Avia-
rocket allows it to insert its payload into the correct, or nearly correct, orbit. GPS is also being used to position the antennas of satellite communication ground stations.\textsuperscript{16}

\subsection*{2.1.2 The Increasing Military Dependence on Space}

As these powerful systems become integrated into military operations, the systems and skills they replace will inevitably atrophy. New capabilities enabled by satellite navigation, reconnaissance, and communication will become the norm. Operations will become dependent on these assets. In addition, procedures and training for operations without satellites will decline. Such equipment and skills will be reduced to the status of an emergency backup system. Later, they will be viewed as unnecessary luxuries. The satellite systems are so much easier and faster to use, not using them (even in exercises) will become a burden. Eventually, the older equipment will be deemed obsolete. The necessary skills to run these older systems will be considered less important. How many members of the Army know how to ride a horse? Analogously, the military will come to depend on space systems, and its ability to function without them will decline.

Maintaining the non-space dependent skills and equipment will also be expensive. In a time of declining military budgets, there will be strong pressure to eliminate redundant non-space dependent systems.

\subsection*{2.1.3 Cables as an Alternative to Satellite Communications}

Concerning the future of satellite communications, some have argued that fiber optical cables will eventually replace satellite communications. Researchers have pointed out that fiber optics are cheaper, even for large volume communications which require special local connections to the long distance network.\textsuperscript{17} But commercial satellite service providers believe that they can compete in the long run with fiber optical

\textsuperscript{16} \textit{Aviation Week} \& \textit{Space Technology} October 26th, 1992, p. 11.

cable.\textsuperscript{18} For military purposes, fiber optics present both advantages and problems. Because the signals are confined to the cable itself, it is much more difficult to intercept or interfere with cable transmissions. But the cable itself is not necessarily more secure.

Undersea cables are vulnerable to being cut by enemy ships and submarines. Cables can also require the consent of third parties to allow war traffic to flow via their cables or territories. At the beginning of World War I, England’s first offensive action was to dredge up and sever all of the German trans-Atlantic cables.\textsuperscript{19} For the duration of the war, all trans-Atlantic German message traffic was sent via radio. These messages were decoded and read by British Naval Intelligence. Today, all U.S. undersea cable is located on coastal nautical charts to prevent fishermen from accidentally damaging cables while dredging for shellfish.\textsuperscript{20} It would be a simple matter for any hostile power with a boat to sail out and cut them.

Cables also lack flexibility. If one is fighting a war in a area with a high volume of phone traffic (like Europe), a fiber cable is likely to be there in the future. But many wars occur in distant places without much warning. Military communications require the ability to suddenly increase the volume of information flowing to and from any place in the world. Satellites are uniquely able to provide this service. Thus, even if fiber optics does undermine the commercial satellite communications market, there will still be a need for military satellite communications.

This is all well and good, provided that our space assets are dependable. Currently, only Russia has the ability to attack U.S. satellites directly with a rather limited ASAT system which may no longer be operational. But as more countries gain access to rocket technology, satellites may become vulnerable. It is possible that the U.S.


\textsuperscript{19}Actually England did not cut one German trans-Atlantic link. This one exception was an American-owned cable running from Africa to Brazil. The British did not rip up this cable for fear of irritating the Americans, but the Eastern Telegraph Co. obligingly severed and wound up 30 miles of the cable at the request of the British Admiralty. See Tuchman, Barbara W. \textit{The Zimmermann Telegram} Ballantine Books, New York, 1958, pp. 10-11.

\textsuperscript{20}Phone conversation with Mr. Hagendorf of the Trans Oceanic Cable Co., sub-contractor to AT&T. Spring 1992.
military may become very dependent on its satellites just as the security of these satellites is threatened.

2.1.4 Summary

Space assets provide real military value. Over time, our military is becoming more dependent on these systems to conduct operations. Therefore, space assets are now and will continue to be important military assets. This means that nations at war with the U.S. will want to neutralize these systems and that the U.S. will want to neutralize any space systems used by its enemies.

2.2 KKV’s the Ultimate Space Weapon

Based on the investigations reported in Chapter 4 and Chapter 5, I claim that the ASAT system of choice in space is the kinetic kill vehicle (KKV). In this section I present the highlights of those investigations. The KKV is effective for three reasons: it is difficult to hide targets in space, kinetic impact kills are impossible to shield against, and orbital mechanics favor the attacker. I examine each of these topics in turn.

2.2.1 The Target Visibility Advantage

Satellites in Earth orbit are, very visible. Satellites in Low Earth Orbit (LEO, 200 to 1,800 km above the surface of the Earth) can be tracked using radar. Satellites in Semi-Synchronous Orbit (SSO, 20,183 km above the surface of the Earth) and Geosynchronous Orbit (GEO, 35,785 km above the surface of the Earth) are detectable using optical instruments. In space, the only way to dissipate the energy absorbed from Sunlight is to radiate it away. Satellites are usually constructed of metallic, reflective materials to keep their temperatures low. Reflective satellites are visible even to low powered telescopes from Earth.

One could imagine constructing a “stealth” satellite by painting it black. With a
special design, the resulting high temperatures could be managed. But high temperature objects (around 405 degrees Kelvin (K), see Section 9.3.2, p. 245) are visible in the Infra-Red (IR) spectrum from Earth and black surfaces radiate very well. In other words, if the satellite is reflective, it is cool but visible in the visible region of the electromagnetic spectrum. If it is absorbent, it is hot and visible in the IR region.

If, however, the stealthy satellite spins or conducts heat well along its surface, then the radiating surface area is increased and the satellite surface temperature drops to 278 K. As long as the satellite is solar powered and conducts heat well, it will stay cool.21 Because the Earth's atmosphere has a "surface temperature" very close to this, it is impossible to pick out the satellite in GEO from the atmospheric IR noise.

But an operational satellite must transmit information. Thus, even if the satellite is black and cool, its radio emissions will give its position away. ASATs do not need to relay information and so they can use these methods to hide from ground-based sensors. If a communications satellite used a laser for downlink (a costly but tested method), it too might hide from terrestrial sensors. Currently only U.S. early warning DSP satellites have laser downlinks built into them.

To track and kill satellites in LEO with a KKV requires only a big radar and a big computer (See Section 9.3.1, p. 241). To track and kill things in GEO requires 5 pairs of IR and optical telescopes, spaced equally around the globe. But this system has limitations. The optical telescopes only work in good weather and only at night.22 This limits their operation to a few hours a day. The IR telescopes require high altitudes and a dry environment. Neither the IR nor the optical telescopes will work in cloudy weather or if the satellite is painted black and spins. In short, this system

21The argument here is that solar panels cannot produce power greater than the sunlight energy shining on it. A problem arises if that power is sent to the core of the satellite and there is a poor thermal connection between the solar panels and the core. Then the core becomes hot and doesn't have sufficient energy to dissipate the heat. But we are talking about satellites that are heavily modified to be stealthy, so I expect that a good thermal connection between the solar panels and the core is an inherent part of the design. If the satellite is nuclear powered, then it is impossible to hide because of the high power density of the reactor produces high temperatures.

is adequate for monitoring and attacking SSO and GEO satellites which do not go to extreme methods to hide.

Those that do use extreme measures are likely to be limited in their functionality. A satellite using a laser downlink must know the location of any receiver on Earth. Further, any receiver on Earth must know the approximate location of the satellite in orbit. This is not a problem for early warning or electronic intelligence satellites because they know always who they want to talk to and where they are. But this would severely limit communications and navigation satellites’ functionality. Navigation satellites must know the location of every one using the satellite navigation system. Area navigation and communications coverage is not an option because if the satellite is “visible” to a wide area, then an enemy can identify its location. If the enemy can identify the direction of any user sending to the satellite, they can determine its approximate location.

I conclude that operational satellites are very difficult to conceal from ground-based observers. Satellites in LEO are visible to radar. Satellites in higher altitudes are visible because of the visible light they reflect and because of the radio transmissions they emit. Measures can be adopted to eliminate both of these signatures, but the operations of any communication or navigation satellite would be highly constrained.

2.2.2 ASAT Detection

Now I discuss detecting ASAT attacks with terrestrial sensors. Satellites in LEO cannot benefit from attack warning because pop-up ASAT\textsuperscript{23} flight times are so low. However, satellites in SSO and GEO (and LEO satellites under co-orbital ASAT attack) can benefit from attack warning.

It may be possible to use the existing U.S. early warning satellites to perform the ASAT attack detection mission instead of creating a new early warning constellation. The early warning Defense Support Program (DSP) satellites detect only high tem-

\textsuperscript{23}A pop-up ASAT attack is an a the most efficient method for attacking satellites. The ASAT is launched straight up as the satellite passes overhead.
perature rocket exhausts. These IR sensors need to be kept cold, but not as cold as the those detecting lower temperature objects. The problem with DSP is that their field of view (FOV) is only large enough to scan the Earth. This allows them to see most rocket activity in LEO, but not at higher altitudes. Since the ASAT would be coasting when not accelerating, its trajectory would be highly predictable. The only time this would change would be if it used its rockets, in which case the DSP satellite could track the change in trajectory as it was initiated. Most ASAT launches from LEO to SSO or GEO would be picked up by the DSP system (see Section 9.3.3, p. 254). But a determined ASAT, using a very expensive launch profile, could avoid the DSP system.

One could also use 2 Long Wave Infra-Red (LWIR) satellites in any orbit 180 degrees apart, to survey everything above LEO. LWIR is what the KKV ASATs use to track their targets. LWIR can pick out even relatively cold objects against the background of space. The problem with LWIR systems is that they need to be kept very cold (2-10 K) to work well, which makes it difficult to achieve a 10 year satellite lifetime. There is hope, however, that new technologies will circumvent this problem (see Section 9.3.2, p. 250). This system could provide high ASAT attack warning.

I can summarize as follows. For offensive KKV attacks against LEO targets, a single ground radar is sufficient. To detect high altitude targets, a global network of optical and IR telescopes would be needed. To detect very stealthy satellites, a LWIR satellite system would be required. The U.S. already possess the limited DSP system, which can detect most ASATs attacking SSO and GEO. For detecting all high altitude ASAT attacks, an LWIR satellite system would be required.

2.2.3 The Impact Kill Advantage

In order to succeed, the KKV must have a homing system capable of achieving impact under high closing velocities (order several km/sec). This gives it a great advantage over its target. The KKV can close with the satellite from a range of angles. Typically, the KKV closes with its target from a range of angles from perpendicular to head-on (although it may be effective at angles of less than 90 degrees). Thus, it can use the
target satellite's own kinetic energy against it.

Even the relatively slow orbital velocity of GEO is enough to give any object explosive kinetic energy. This means that even small interceptors can destroy very large satellites if they collide at a high relative velocity. It also means that shielding is useless. At a relative velocity of 4-8 km/sec, an object of significant mass (order 1 kg) will penetrate any realistic shield. Thus, a KKV can be much smaller and lighter than the satellite it attacks. Further, the KKV need not carry a destruction mechanism. The satellite's orbital velocity, imparted to it by its launcher at great cost, is the destruction mechanism.

2.2.4 The Orbital Mechanics Advantage

Just as an upwind position gives advantages to sailing ships in battle, and just as higher altitude gives advantages to fighter aircraft engaged in a dog fight, so the medium of space confers certain advantages.

Hit-to-kill KKV ASATs only need to be able to reach their target. They do not have to sustain an orbit. A pop-up attacker simply launches straight upwards, reaching the target satellite's orbital altitude just as it passes overhead. This is like dropping a rock from an overpass onto a car on a freeway. Timing is crucial. Although the rock is moving slowly, the car's speed creates a violent impact.\(^\text{24}\)

Since KKV ASATs are not required to stay in orbit, they need only pay the cost of reaching the satellite's altitude. In contrast, a satellite must reach orbital altitude and orbital velocity. Thus, an ASAT attacking targets in LEO has a great advantage in terms of rocket thrust required to make its attack versus the rocket thrust required to place a satellite into orbit.

This advantage diminishes significantly as the targets move up to GEO however.

\(^\text{24}\)My committee chairman asked: "What if the rock lands on the roof of the car?" My answer is because the car is moving so fast, the rock cannot land on the roof, it can only scrape off the paint as the car flashes by. This may do some damage to the car, but not critical damage. With a KKV attack, the ASAT will almost certainly either hit the front of the satellite or miss completely. In the very unlikely case that it scapes the side of the target, there is a lesser chance of doing damage. The side plate of the satellite will explode, but toward the back end of the satellite. It is not clear that this will do critical damage, depending on how far back on the satellite the point of impact is.
The costs of reaching that altitude are higher and the required orbital velocity is lower. Also, at GEO, pop-up attack is not practical. The attacker must launch from the Equator and from a particular longitude to execute a pop-up attack.\textsuperscript{25} If the launch site is either not at the Equator or not at the correct longitude, which is highly likely, then the attacker must pay a large price countering the effects of the Earth's rotation to execute a pop-up attack against a GEO target. Realistically, the attacker will almost certainly launch into LEO and then use a Hohmann transfer orbit\textsuperscript{26} for a head-on attack. This allows the attacker the flexibility to launch from anywhere on Earth, and allows for a fairly efficient ascent trajectory. While the difference in velocity between Geosynchronous Transfer Orbit (GTO) and GEO is very small, the impact advantage remains, because the KKV can execute a head-on attack (see Chapter 4).

Thus, we see that a KKV can destroy satellites that are much larger that it is, and in most cases, with less rocket thrust than the target used to reach orbit. I keep speaking of the KKV's advantages in terms of rocket thrust, but what does this mean in terms of dollars? This is the topic of the next subsection.

2.3 Launch Costs: Rockets and Gun Launchers

In this section I estimate the actual costs of getting satellites and ASATs into space. Currently the only technology for launching objects into LEO is the chemical rocket. I discuss these first. I also examine how a new launch technology, a gun launcher, might compete with these costs.

Rockets

Rockets are the primary means of transport in space today. They provide acceleration (change in velocity or $\Delta V$). Everything in Earth orbit must constantly move to

\textsuperscript{25}The launch site longitude will be to the east of the target. As the ASAT ascends, coriolis forces will cause it to drift westward. This is because the velocity of an object on the Equator is much less than the orbital velocity required to maintain GEO.

\textsuperscript{26}This is the most efficient path between two circular orbits using rocket thrust at a means of propulsion.
maintain that orbit. Getting around in space is a matter of changing velocity to move from one orbit to another.

Rockets provide $\Delta V$ by igniting fuel. The combustion products move backward, which results in the rocket accelerating forward. It would be most efficient if all the fuel could be burned instantly, in one big explosion, but this presents certain engineering difficulties. The fuel must be burned slowly enough to allow the rocket engine to contain and direct the blast. The trouble is, as fuel is burned, the unburned fuel and the rocket motor are accelerated along with the payload. This leads to exponential growth of fuel cost, and therefore rocket size, as required $\Delta V$ increases. In other words, it takes more than twice as much fuel to go from 0 km/sec to 2 km/sec than it does to go from 0 km/sec to 1 km/sec. This is why small changes in required $\Delta V$ can lead to big changes in rocket size.

**Rocket Launch Costs**

Total launch costs includes all launch services, integration, and testing, excepting the cost of the actual satellite. My estimate of the cost per kg to reach LEO (see Section 6.5.2 p. 194) is:

$$LEO\;\text{Launch\;Cost}\;\left(\$/kg\right) = 26,400 - 7,750 \times \log_{10}\left(\frac{\text{Payload\;kg}}{100}\right)$$  \hspace{1cm} (2.1)

Note that larger payloads cost less per kg than small ones because of economies of scale. But what we really want is an equation that will provide costs given a payload and a mission requirement. Some missions, such as a pop-up LEO ASAT attack, will require less thrust. Other missions, such as putting satellites into GEO, will require more thrust. In both cases, we can use LEO equivalent mass to determine the rocket cost. Let’s examine each of these cases individually.

My cost model for pop-up attacks bases costs on equivalent LEO mass. I can compute the payload and $\Delta V$ required for a pop-up mission. If I know the rocket mass required to perform a mission, I can ask: how much mass could this same
rocket get into LEO? Based on this LEO equivalent mass, I can estimate the cost of the rocket required to perform any given LEO attack.

I can compute the cost of going to GEO this way. In this case the mission requirement is greater than that needed to LEO. I simply add the necessary rocket mass to the total LEO payload to get the actual payload to our destination. I can estimate the cost of a rocket required to get our payload from LEO to GEO using the same method. Since I know the mass of such a rocket, I add this to our payload to determine the total mass that must be lifted into LEO. It turns out that the actual cost of the LEO-to-GEO rocket is very small compared with the cost of lifting it into LEO, so I can ignore the cost of the additional rocket.

Going from LEO to GEO requires a rocket with a payload percentage of roughly 25% (based on averages of liquid and solid booster performance). Thus, a rocket capable of putting 4 kg into LEO is also capable of carrying another rocket capable of putting 1 kg into GEO from LEO. If I ignore the cost of the additional rocket, I can use this fact to determine the cost of reaching GEO. Simply multiply the payload by four (the LEO equivalent mass) and plug it into the above equation. The actual cost per kilogram to GEO is slightly less than four times the cost per kilogram to LEO because larger payloads are slightly cheaper on a per kilogram basis.

**Gun Launcher Costs**

Gun launchers add an additional element to the cost equation. Because no gun launcher exists, costs are unknown. But they are expected to reduce launch costs to LEO by two orders of magnitudes. Consider these reductions in comparison to the large boosters, which already have comparatively low launch costs. We are talking about hundreds of dollars per kg instead of tens of thousands. I estimate a launch cost of $300/kg.\(^{27}\) In the next section I use these methods to estimate on-orbit costs.

---

\(^{27}\)Cost estimates depend on system usage: the more use, the lower the costs per kilogram. This is because much of the cost goes to building the system. The lowest estimate I’ve seen quoted is $300/kg (See Henderson, Breck W. “Ram Accelerator Demonstrates Potential For Hypervelocity Research Light Launch” *Aviation Week & Space Technology* September 30th, 1991, pp. 50-51). I have chosen the low estimate to see how much of an impact the gun launcher might have.
of actual satellites.

2.4 Cost Comparison

In this section I compute the costs of putting satellites into orbit and the costs of shooting them down. Currently the offense has a great cost advantage. However, with the introduction of micro-satellites, this balance can be shifted to favor the defender slightly.

In the previous section, I presented a working model to determine the costs of putting satellites and ASATs into space using both conventional rockets and gun launchers. But I also need to know the weights and costs of the satellites and the ASATs themselves. The costs of U.S. military satellites are known, so I use them as a basis for target satellite costs. The most expensive LEO imaging satellites (the KH-11s) run $500 million each and weigh 17,000 kg.\textsuperscript{28} A GEO DSCS III communication satellite costs $90 million\textsuperscript{29} and weighs 1150 kg.\textsuperscript{30} The jam resistant (through adaptive nulling) Milstar communication satellites are expected to weigh 4,500 kg and to cost $515 billion each.\textsuperscript{31}

I also need to be able to assess the costs of micro-satellites. I estimate that small LEO communication micro-satellite will cost $400,000 and weigh less than 10 kg.\textsuperscript{32} This is only a very rough estimate for microsatellite costs. The micro-satellite I am using as the basis for our estimates was built by hand and in low numbers. It was a simple store-and-forward communications system with a limited message memory.

\textsuperscript{28}Covault, Craig “Recon Satellites Lead Allied Intelligence Effort” \textit{Aviation Week & Space Technology} February 4th, 1991, pp. 25-26 and “Soviets Claim Reconnaissance Satellite Launched by Atlantis Has Failed” \textit{Aviation Week & Space Technology} March 26th, 1990, p. 23.


\textsuperscript{30}Kolcum, Edward “Atlas 2 Launch Bolsters Military Spacecraft Network” \textit{Aviation Week & Space Technology} February 17th, 1992, p. 64.


The micro-satellite system the U.S. will need in order to compete with pop-up KKV ASATs will have to be more capable than this. On the other hand, it could be mass produced, which would yield economies of scale. The increased capability would tend to increase both its cost and weight, but mass production would tend to reduce cost and weight. I use this data point because it is the only one I have, but it should be understood that a militarily useful micro-satellite will probably cost more.

I also need an estimate for the cost and mass of a KKV warhead. The U.S. has already created an ASAT weighing as little as 25 kg.\textsuperscript{33} As for cost, I can look to estimates of Brilliant Pebbles' costs. Brilliant Pebbles perform essentially the same function as a pop-up ASAT: high speed kinetic intercept. A Brilliant Pebble is supposed to weigh 4.5 kg and cost roughly $1 million.\textsuperscript{34} In what follows, I assume that ASATs cost $1 million and weighs 4.5 kg.

Nuclear ASATs are more difficult to quantify. The marginal cost of a nuclear weapon to the U.S. is roughly $2 million (see Section 9.6.1, p. 269). This is probably the lowest cost of any nuclear power. The marginal cost for other nations, especially emerging nuclear powers, could be substantially more.

I can now compare the costs of putting a system in orbit with the cost of shooting it down, both with and without a gun launcher. The results are shown in Table 2.1.

Some might point out that the cost of destroying a satellite should be higher than listed because ASAT missiles are not 100% reliable. With a less than perfect reliability, an additional ASAT would occasionally be required to kill the target when an ASAT failed, increasing costs on average. But this same reliability also applies to the boosters that launch the satellites. Thus, if one assumes that the reliability of satellite boosters and ASAT missiles are comparable, then reliability does not affect the cost comparison.

Table 2.1 illustrates that the current cost exchange balance favors the attacker. A


KH-11 satellite costs 634 times more than the rocket-based system required to destroy it. The DSCS III satellites costs 68 times more than the rocket-based ASAT system required to destroy it.

In contrast to existing satellites, micro-satellites might cost roughly the same as the ASATs required to destroy them. In other words, a defender could launch micro-satellites for roughly the same cost as an attacker would pay to destroy them. The current estimate in Table 2.1 is that micro-satellites would have roughly a factor of two to three cost advantage. But the cost of the micro-satellite and the cost of the KKV are only rough estimates, so the exact cost relationship is only a guess. We are more certain that their costs would be roughly the same order of magnitude, which implies that micro-satellites could hold their own against KKV s on a cost basis.

If both sides are willing to spend infinite amounts of money, then the eventual outcome depends on the relative launch capacity of the attacker and defender. If the attacker can launch faster, the micro-satellite population will gradually decline. If the defender has a higher launch capacity, then the defender can maintain the population or even increase it.

This illustrates another advantage of micro-satellite constellations: they degrade gracefully. Since many of them are launched together (more on this below), they take a long time to destroy and their performance declines in proportion to the percentage of her satellite population destroyed. This allows the defender to replace satellites under attack while maintaining functionality.

An additional advantage of micro-satellites is that they can be deployed in large numbers from a single booster. This can significantly decrease launch costs per kg. Thus, the table entry lists rocket-launched micro-satellite costs for one micro-satellite per rocket and for 100 satellites per rocket.

To make communications micro-satellites work, they have to be launched in large numbers. This is because each micro-satellite would have a limited capacity (because of its size) and a limited footprint (because of its low orbit). A population of 400 randomly orbiting satellites will provide, on average, 95% global coverage at any given time. 400 micro-satellites can be purchased and put into orbit for the same cost as
### Table 2.1: Costs of Targets and ASATs

<table>
<thead>
<tr>
<th>System</th>
<th>Weight in Kg</th>
<th>System Cost $ Millions</th>
<th>Launch System</th>
<th>Launch Costs $ Millions</th>
<th>Total Cost $ Millions</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO Targets and ASATs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KH-11 in LEO</td>
<td>17,000</td>
<td>500</td>
<td>Rocket</td>
<td>150</td>
<td>650</td>
</tr>
<tr>
<td>Microsat in LEO</td>
<td>10</td>
<td>0.400</td>
<td>1/Rocket</td>
<td>0.340</td>
<td>0.74</td>
</tr>
<tr>
<td>Microsat in LEO</td>
<td>10</td>
<td>0.400</td>
<td>100/Rocket</td>
<td>0.186</td>
<td>0.586</td>
</tr>
<tr>
<td>Microsat in LEO</td>
<td>10</td>
<td>0.400</td>
<td>Gun</td>
<td>0.003</td>
<td>0.40</td>
</tr>
<tr>
<td>LEO KKV ASAT</td>
<td>4.5</td>
<td>1.0</td>
<td>Rocket</td>
<td>0.16</td>
<td>1.2</td>
</tr>
<tr>
<td>LEO KKV ASAT</td>
<td>4.5</td>
<td>1.0</td>
<td>Gun</td>
<td>0.0014</td>
<td>1.0</td>
</tr>
<tr>
<td>LEO Nuclear ASAT</td>
<td>380</td>
<td>2+</td>
<td>Rocket</td>
<td>8.3</td>
<td>10.3+</td>
</tr>
<tr>
<td>LEO Co-Orbital ASAT</td>
<td>2,500</td>
<td>?</td>
<td>Rocket</td>
<td>40</td>
<td>40+</td>
</tr>
<tr>
<td>(via poles to avoid DSP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GEO Targets and ASATs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSCS III in GEO</td>
<td>1150</td>
<td>90</td>
<td>Rocket</td>
<td>62</td>
<td>152</td>
</tr>
<tr>
<td>Milstar in GEO</td>
<td>4,500</td>
<td>515</td>
<td>Rocket</td>
<td>160</td>
<td>675</td>
</tr>
<tr>
<td>GEO KKV ASAT</td>
<td>4.5</td>
<td>1</td>
<td>Rocket</td>
<td>0.58</td>
<td>1.6</td>
</tr>
<tr>
<td>GEO KKV ASAT</td>
<td>4.5</td>
<td>1</td>
<td>Gun</td>
<td>0.0054</td>
<td>1.0</td>
</tr>
<tr>
<td>GEO Nuclear ASAT</td>
<td>380</td>
<td>2</td>
<td>Rocket</td>
<td>26</td>
<td>28</td>
</tr>
<tr>
<td>GEO Co-Orbital ASAT</td>
<td>2,500</td>
<td>?</td>
<td>Rocket</td>
<td>108</td>
<td>108+</td>
</tr>
<tr>
<td>GEO Co-Orbital ASAT</td>
<td>2,500</td>
<td>?</td>
<td>Rocket</td>
<td>250</td>
<td>250+</td>
</tr>
</tbody>
</table>

We have seen that only micro-satellites would be roughly equivalent in cost to the best ASATs. Thus, the only way to illuminate the offensive cost advantage would be to move all our space functions into micro-satellites—if such a conversion were possible. Next I discuss further cost advantages provided by a gun launcher.

#### 2.4.1 Gun Launcher Advantages

A truly low cost gun launcher could shift the cost balance toward either side. A gun launcher can reduce the costs of placing micro-satellites in LEO. In is impractical to launch large GEO satellites with gun launchers because they are too large for the gun systems currently being designed.

A gun launcher reduces the cost of a LEO ASAT attack by 17%, and it reduces the costs of a GEO ASAT attack by 38%. The advantages for micro-satellite launches ranges from 32% to 46%, almost a factor of two. In other words, gun launchers are
move valuable to satellite defenders than to attackers. Even though launch costs are dramatically reduced, on-orbit costs\textsuperscript{35} only drop by a factor of two. This is because, although the launch costs are sharply reduced, system costs remain the same, so total costs are not reduced by two order of magnitudes. These advantages, however, depend entirely on gun launch costs being as low as its proponents claim. Launch systems have historically ended up being more expensive than originally claimed.

If the gun launcher cost is as low as claimed, then it is an advantage, especially if one can deny an opponent use of their gun launcher. Another potential advantage of a gun launcher is that launch rates can be very high, depending on the technology employed. As we stated above, in a situation where an attacker is trying to destroy large constellations of micro-satellites with large numbers of ASATs, launch rates will determine the outcome if both sides have considerable financial resources.

2.4.2 Destroying Gun Launchers

How many gun launchers are there likely to be, and how easily can they be destroyed? Because of the expense (roughly $7 billion)\textsuperscript{36} the U.S., or any other nation, is unlikely to have more than one or two gun launchers (a second one, perhaps, to launch into polar orbits). The low cost of launching with a gun launcher would reduce interest in existing rocket launch systems. Thus, other nations are more likely to depend on the U.S. gun to launch their satellites. Only those countries rich enough or hostile enough to the U.S. might build their own, but again only one or two launchers would be likely. These guns would make very attractive targets in a war. In order to be practical, gun launchers have to be constructed at high altitude and at an angle of at least 30 degrees. Thus, mountains or high plateaus would be required. The U.S. is fortunate in that it has many good mountains in its interior. Unlike existing coastal launch facilities, it would be fairly easy to protect this asset from attack. Obviously, should the U.S. ever build a space gun, it should choose a site away from any ocean,

\textsuperscript{35}On-orbit costs are the total costs of a satellite in orbit. That is satellite costs plus launching costs.

\textsuperscript{36}Henderson, Breck W. “World’s Largest Light Gas Gun Nears Completion at Livermore” \textit{Aviation Week \& Space Technology} August 10th, 1992, pp. 57-59.
not in Hawaii as some have proposed.\textsuperscript{37}

Some potential space power nations are not so lucky. If Japan were to build such a gun, it would be close to the ocean. Everything in Japan is close to the ocean. Defending air space and striking deep into others’ air space is something that the U.S. military does well. An air strike using precision guided munitions (PGMs) or a cruise missile strike could neutralize an opponent’s gun. This would be more difficult if the gun were actually built into the interior of a mountain. In that case it would not be necessary to destroy the gun. Simply collapsing the opening at the top of the mountain would be enough.

Summary

Gun launchers might affect the competition between space powers by decreasing micro-satellite on-orbit costs by as much as a factor of two. The impact on KKV ASAT kill costs is less, but still significant. An offensive nation, attempting to destroy a micro-satellite population will have a strong incentive to destroy the opponent’s gun launcher. Therefore, air or missile strikes against gun launchers themselves might grow out of a space conflict. Because gun launchers must be placed in high-altitude regions, any nation with interior mountains or high plateaus will have a defensive advantage because these air strikes will be more difficult to mount. If the U.S. ever builds a gun launcher, it should choose a site well inland.

2.5 Decoys, Anti-Anti-Satellites and Self-Defending Satellites

Thus far I have been assuming that satellites do not attempt any counter measures against the ASATs, such as decoys, maneuver, and self defense missiles. It is now time to examine this possibility.

\textsuperscript{37} “Zap! Coil guns offer to orbit small cargoes on a regular schedule” Scientific American April 1990, p. 22.
2.5.1 Decoys in LEO

As we have seen, the cheapest, most effective form of destruction in space is the kinetic kill vehicle (KKV). Satellites in LEO and ULEO are particularly vulnerable to this form of attack. They cannot run and they cannot hide.\textsuperscript{36} In terms of system and launch costs, an attacker can destroy satellites in this region at a cost hundreds of times less than that required by the defender to place them there. We shall see that in LEO it is difficult to defend against KKV attack.

Decoys are not terribly effective in LEO because of the short ascent times of kinetic ASATs (on the order of ten minutes for a minimum energy trajectory). There is little time to detect the attack and command the satellite to deploy decoys. ASAT ascent times can be further reduced by using larger launch rockets or by launching from flying aircraft (as the U.S. MHV system currently does).

If decoys are deployed when the satellite is launched, they can be distinguished from the actual target given enough time. This is because only the satellite emits radio signals. Remember that decoys weigh around one kg, and that micro-satellites would probably weigh less than 10 kg. If the decoys are improved to transmit false radio signals, they might as well be micro-satellites. Finally, in LEO, decoys would have a much higher drag than the satellite, so their orbital lifetime would be much less.

In addition, because of the low KKV ascent times, defensive maneuver is not effective. The satellite has very little time to move any appreciable distance between the time the ASAT launch is detected and the time the satellite is struck by the ASAT.

2.5.2 Decoys in GEO and SSO

Almost all targets in SSO and GEO would be large, heavy satellites. This is because micro-satellites are really only practical in LEO, and cannot function at high altitudes.

\textsuperscript{36}It is impossible to hide in LEO from radar and optical sensors. Satellites in higher altitudes can hide from ground-based IR sensors (see Section 9.3, p. 241), but with diminished functionality for communication and navigation functions. No satellite can hide from space-based LWIR sensors.
I was surprised to learn that this is not due to communications power requirements. For a given area, radio transmission power requirements do not go up significantly with altitude. This is because the required angular area of coverage decreases as the range and altitude increase. Thus, power requirements do not increase significantly. But what does increase significantly are antenna requirements. A satellite in LEO can use an omni-directional antenna which is small and cheap. The micro-satellite can tumble or use a boom to maintain one axis stability. In contrast, satellites in SSO and GEO must have directional antenna. At high altitude, a focusing antenna is required to channel radiated power into a particular spot. Thus, high altitude satellites must be three-axis stabilized and have large antenna with mechanical or electronic focusing systems. All this requires additional hardware: navigation system, pointing and tracking system, satellite maneuver systems.

It is possible to place micro-satellites into GEO, but directional antenna requirements push the satellite weight up to unacceptable levels. Thus, micro-satellites remain a LEO-only concept.

Satellites in SSO and GEO are vulnerable to kinetic attack because they are large. However, high altitude does provide the defender with some advantages. While hiding is difficult, dispensing decoys and defensive maneuvers are much more effective in SSO and GEO. If the attacker is detected, a defending satellite has time to run, dispensing decoys as it goes. This complicates life for the attacker, resulting in the attacker having to pay a greater price to kill a satellite than the defender paid to put it there.

Decoys weigh about one kilogram each,\textsuperscript{39} while ASATs would weigh at least five kilograms. Thus, from a launch cost viewpoint, the defender has an advantage of five to one. From a total system cost viewpoint, this jumps to 10 to one, since the ASAT costs as much to launch into GEO as it does to produce. In contrast, decoys are

\textsuperscript{39}Decoys simulating nuclear re-entry vehicles are expected to weigh about one Kg. I assume a similar weight would be required to simulate a target satellite. Why? RV's are only slightly smaller than most satellites. Most penetration aids are designed to confuse ABM systems during the time when the RV and decoys are in space. Since the satellite decoy performs a similar function for a similarly-sized object under similar environmental conditions, I assume that its weight is similar. In the cases where the satellite being simulated is substantially larger than an RV (for example a Milstar satellite) I assume a heavier decoy is required.
very inexpensive to produce and can be launched cheaply with the satellite. But this must be traded off against the initial cost advantage the attacker has before decoys are introduced.

For example, without decoys, the attacker cost advantage against a DSCS satellite is roughly 70. If the defender brings along a hundred one kilogram decoys and dispenses them on warning of an attack, the attacker will have to pay a higher cost to guarantee destruction of the satellite than the defender paid for the satellite and its launch into orbit.

If the attacker can take his time, he should be able to distinguish decoys from the actual target. This is because the decoys will drift away as the satellite makes corrections to remain on station. Also the satellite will emit radio transmissions. The defender could turn off the satellite, but then the attacker has effectively neutralized the satellite, since transmission of information is the whole purpose of military satellites.

One could imagine the attacker developing a more sophisticated ASAT that matches orbit with the target satellite and its decoys and simply waits for one of its targets to begin transmitting. When it does, the ASAT attacks that target. The target would have little time to transmit since the ASAT would be close by, ready to attack. Of course, the ASAT would have to carry a destruct mechanism of some kind since the orbits of both target and ASAT would be closely matched, the ASAT could not use kinetic energy to destroy it.

Finally, in order to see the attack coming, the defender must be able to track ASATs as they emerge from LEO to GEO and SSO. This will require a space-based tracking system. With such a system, and with enough decoys, the defender should be able to defend his satellites in the short term. Over an extended period of time however, the attacker can send single ASATs to force the target to dispense decoys. When the target runs out of decoys, a single ASAT will be sufficient to destroy the target.
2.5.3 Self Defense and Maneuver in GEO or SSO

What about self-defense? Yes, GEO satellites might be able to defend themselves with Anti-Anti-Satellites (AASATs). But only on equal cost terms with the attacker since any kinetic kill vehicle orbiting with the satellite will have added weight and cost to the payload. The AASAT will probably cost as much as the ASAT. The AASATs launch cost would probably be lower since they would be launched with a large payload, reducing per kg costs. However, these AASATs would also have to remain operational on orbit for long periods of time, which would increase cost and weight. Eventually, if multiple ASATs were fired, the supply of defending AASATs would be exhausted. Again, a space-based IR surveillance system would be required to see an ASAT coming.

Thus, AASATs only slightly dilute the attacker advantage. The AASAT and ASAT are on equal terms, but the satellite is still much more expensive than the ASAT which eventually kills it. AASATs force the attacker to send more than one ASAT against the satellite, and can delay the satellite's destruction, but they do not fundamentally affect the offensive advantage.

As I point out in Chapter 4, defensive maneuver against an ASAT with a limited closing velocity capacity (a co-orbital ASAT) would be effective in SSO and GEO. But against a high velocity interceptor, this is not the case. The best one can accomplish with defensive maneuver is to delay intercept and to force the attacker to pay an equal $\Delta V$ price (see Section 4.3, p. 136). I discuss co-orbital ASATs in the next section.

What about a ground-based AASAT interceptor destroying the ASATs before the ASAT reaches its target? It is unlikely that a system of ground-based anti-anti-satellites would be practical. In addition to needing a space-based IR system to monitor all ASAT movements, one would need an effective method of shooting them down. As I note in Chapter 4, getting somewhere in orbit quickly costs a great deal of rocket mass. A ground-based AASAT would be a hopelessly inefficient weapons system.

Thus, self-defense and maneuver are tactics that exact an equal price from attacker
and defender; they don't provide a significant advantage for either side. This leaves decoys as the best defense. They do provide leverage for the defense, but only if the attacker must destroy the target quickly.

2.6 Alternative ASATs

Now I examine alternative space weapons. In this section I examine the pros and cons of co-orbital ASATs and the use of communications satellites as downlink jammers. In Sections 2.7 and 2.8 I discuss laser ASATs and nuclear ASATs.

2.6.1 Co-Orbital ASATs

Co-orbital ASATs are not very effective (see Chapter 4 for more details). Defenders can effectively maneuver, even in LEO, because the ascent time is large. Also, defensive decoys are effective. In order to perform these counter measures, however, a global LEO network is needed (the U.S. already has this) to warn targets in LEO. In order to warn satellites in GEO, a space-based IR network of scanners will be needed (the existing DSP satellites can be configured to track in-orbit rocket motor burns, up to LEO altitude). The one point in favor of co-orbital ASATs is that they are easier to build than a high velocity interceptor. The only foreign ASAT in existence today is Russia's co-orbital ASAT. Let's examine the co-orbital ASAT in more detail.

A KKV is capable of intercepts at closing velocities on the order of 10 km/sec. Without this ability, targets become more difficult to reach. A closing velocity limited interceptor must co-orbit with the target rather than pop up, so the booster must be larger. Thus, not having a homing vehicle increases the required rocket size and cost.

When attacking targets, the interceptor must orbit in the same direction as the target, not head-on. This means that targets can be defensively maneuvered, forcing the attacker to make greater expenditures of $\Delta V$ per kilogram than the defender does (see Chapter 4). It also delays intercept and allows more time for decoys to be deployed. The combination of attack detection, decoys, and defensive maneuver can shift the cost trade-off in favor of the defender at any altitude, even if the defender
is using large expensive satellites.

All this assumes that the defender has many decoys, that the attacker has a co-orbital ASAT detection system, and that the attacker must kill the satellite quickly. But, as I noted above, over a lengthy campaign, the decoy advantage diminishes. Without that advantage, the attacker can probably afford to pay additional maneuver costs and still be at a cost advantage, depending on the size and cost of the co-orbital ASAT.

On balance, a co-orbital ASAT is not very practical. At most, its cost advantage is two to one over the most expensive satellites, and it is at a cost disadvantage compared with other satellites. It is vulnerable to detection, decoys, and defensive maneuver. The only reason to build a co-orbital ASAT is if one cannot or will not use nuclear weapons in space and if one does not have the necessary technology to build KKV ASATs.

2.6.2 GEO Communications Jammer

An alternative to destroying a communications satellite is to jam its signal. As I note in Chapter 9, the satellite down link is the weakest link in the communications chain. The problem, from a jammer’s viewpoint, is getting a jammer next to the satellite in GEO. One way to do this is to maneuver a communications satellite already in GEO next to the hostile one and jam the downlink.

If the U.S. is facing an opponent with only one or two GEO satellites, this might be an acceptable option. By designing it’s military communications satellites to emit signals along a large range of frequencies, the U.S. could provide itself with a set of potential GEO jammers one or two of which could be sacrificed during war time to jam the communications of the enemy.

Of course, this action really only makes sense for a small threat. If the opponent has many satellites, building an ASAT would be a much more cost effective approach. I discuss this in more detail in Section 3.3.10, p. 97.
2.7 Laser ASATs

Two major contenders for ASATs prove to be poor investments. These technologies are lasers and nuclear weapons. In this section I focus on lasers. In the next section I discuss nuclear ASATs. While certain inexpensive precautions must be taken to harden satellites against weak lasers and distant nuclear detonations, once this is done these systems do not currently represent a significant threat.

Let us first consider space-based laser ASATs. These systems (which have not yet been built) seem attractive. They could kill at a distance, and laser beams have a very low time of flight to a target. This gives the space-based laser ASAT obvious advantages over kinetic systems. The system could be a multi-shot weapon and could be used to kill several targets. It could also defend itself from KKV’s by melting them before impact. KKV’s require corrective maneuvers until just before impact (where correction are no longer effective because of the high closing velocities). Disabling the ASAT control mechanism before impact would make these corrections impossible, causing the KKV to miss its target.

However, it is possible to shield KKV’s against the effects of laser illumination, at least temporarily. This allows the KKV time to kill the laser based ASAT. In terms of both system cost and launch weight, the shielded KKV is always superior to the laser based ASAT. See Section 7.1, p. 197 for more details. I conclude that space based lasers are a poor investment because they are vulnerable to shielded KKV’s.

2.7.1 Ground-Based Laser ASATs

If space-based lasers are ineffective, what about ground-based lasers? Would they do better? I investigate this question in Section 7.2 (p. 201), and summarize the results here. Table 2.2 lists satellite vulnerability to ground-based lasers at various altitudes and under various assumptions. It is assumed that all satellites, even “unshielded” ones, are hardened against low power laser attacks. This means that a satellite will require 5 Watts per square centimeter (W/sq-cm) illumination to be destroyed. A shielded satellite will require almost 600 W/sq-cm to destroy.
<table>
<thead>
<tr>
<th>Assumptions: Target Shielded Orbit Target?</th>
<th>Conclusions mirror fluence limits:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$W \text{ cm}^2$ $W \text{ cm}^2$ $mW \text{ cm}^2$</td>
</tr>
<tr>
<td>10m Mirror, No Adaptive Optics</td>
<td></td>
</tr>
<tr>
<td>LEO No</td>
<td>Safe – –</td>
</tr>
<tr>
<td>LEO Yes</td>
<td>Safe – –</td>
</tr>
<tr>
<td>ULEO No</td>
<td>Safe – –</td>
</tr>
<tr>
<td>ULEO Yes</td>
<td>Safe – –</td>
</tr>
<tr>
<td>SSO No</td>
<td>Safe – –</td>
</tr>
<tr>
<td>SSO Yes</td>
<td>Safe – –</td>
</tr>
<tr>
<td>GEO No</td>
<td>Safe – –</td>
</tr>
<tr>
<td>GEO Yes</td>
<td>Safe – –</td>
</tr>
<tr>
<td>4m Mirror, Adaptive Optics</td>
<td></td>
</tr>
<tr>
<td>LEO No</td>
<td>Vul Vul Vul</td>
</tr>
<tr>
<td>LEO Yes</td>
<td>Safe Vul Vul</td>
</tr>
<tr>
<td>ULEO No</td>
<td>Vul Vul Vul</td>
</tr>
<tr>
<td>ULEO Yes</td>
<td>Safe Vul Vul</td>
</tr>
<tr>
<td>SSO No</td>
<td>Safe 1.14 1.14</td>
</tr>
<tr>
<td>SSO Yes</td>
<td>Safe Safe 136</td>
</tr>
<tr>
<td>GEO No</td>
<td>Safe 3.57 3.57</td>
</tr>
<tr>
<td>GEO Yes</td>
<td>Safe Safe 426</td>
</tr>
<tr>
<td>10m Mirror, Adaptive Optics</td>
<td></td>
</tr>
<tr>
<td>LEO No</td>
<td>Vul Vul Vul</td>
</tr>
<tr>
<td>LEO Yes</td>
<td>Vul Vul Vul</td>
</tr>
<tr>
<td>ULEO No</td>
<td>Vul Vul Vul</td>
</tr>
<tr>
<td>ULEO Yes</td>
<td>Safe Vul Vul</td>
</tr>
<tr>
<td>SSO No</td>
<td>Safe Vul Vul</td>
</tr>
<tr>
<td>SSO Yes</td>
<td>Safe 21.6 21.6</td>
</tr>
<tr>
<td>GEO No</td>
<td>Safe Vul Vul</td>
</tr>
<tr>
<td>GEO Yes</td>
<td>Safe 68.0 68.0</td>
</tr>
</tbody>
</table>

Table 2.2: Ground-Based Laser ASAT Alternative Future Requirements

Table Notes: Unshielded targets require 5 W/sq-cm to be destroyed. Shielded targets require almost 600 W/sq-cm to be destroyed. Only 84% of laser energy reaches the diffraction spot used to determine lethal area.

Table Abbreviations:
Vul: satellite is vulnerable given current laser power of 2 MW.
Safe: satellite is safe regardless of improvements in power level.
Number: factor by which current laser power must be upgraded; current technology is limited to a factor of 5 increase.
Safe (Number): this satellite would be vulnerable, but the mirror limit of 20 Tera Watts ($1 \times 10^7$ more than current lasers) limits the power increase.
Table 2.2 is divided into three sections. Each makes different assumptions about mirror sizes and adaptive optics. Within each section, each row of the table refers to a particular target orbital altitude, either shielded or unshielded. I can compute the required laser mirror illumination to deliver enough energy to kill the satellite under the given conditions.

The conclusions shown in Table 2.2 are based first on whether or not the mirror illumination is above any of three thresholds. At 0.19 W/sq-cm, thermal blooming becomes significant, but can be corrected for with predictive modeling and adaptive optics. At 340 W/sq-cm, predictive models are unlikely to overcome thermal blooming. At 20 mW/sq-cm, the threshold where cooled laser mirrors begin to break down is reached.

If the mirror illumination required to deliver enough power to destroy the satellite is above any of these thresholds, then we conclude that the target is safe. That is, it cannot be destroyed under those circumstances. If the mirror fluence is below the threshold, and the total power is below 2 million Watts (mW), then we conclude that the target is vulnerable given current laser power technology. Finally, if the mirror fluence is not a problem, but the total laser power is above 2 mW, I state the factor by which current laser power technology will have to be improved in order to destroy the target.

Although work on ground-base lasers seems a poor investment, one cannot guarantee that it will succeed or fail. Sudden simultaneous advances in high powered adaptive optics, atmospheric modeling, and laser power might occur. If this happens, the builder will be able to threaten every satellite in the sky. Under certain conditions, even a shielded satellite at any altitude become vulnerable. Under other conditions, the lower satellites will become vulnerable first, while satellites in SSO and GEO might survive with heavy shielding. Alternatively, it may be impossible to destroy any satellites because adaptive optics cannot be made to work at high power levels.

\[^{40}\text{I assume that the satellite is at its lowest altitude, that is, directly overhead.}\]
Recommendations

I believe ground-based laser ASATs are a poor investment for the U.S. for three reasons. First, as I have already pointed out, the technology is uncertain. We might spend a great deal of money only to find out that we cannot disable satellites with ground-based lasers.

Second, even if the laser system works, it probably will be a wasteful duplication. The U.S. already has more offensive capability than it needs, and is in the process of developing newer KKV systems. The only case where a laser system would provide a substantial increase in offensive capability is if a hostile nation developed extensive satellite facilities to support its military, invested in micro-satellites, and invested in low cost launch technology (possibly a gun launcher). Under these conditions, U.S. KKV systems would be on an equal footing with enemy satellites, while a laser ASAT would still have an overwhelming advantage. But short of this extreme scenario, a laser ASAT would provide little additional offensive force.

Third, successful development of a laser ASAT would show the way to other nations to develop their own systems. Knowing that a thing is possible increases the chances of doing it as well as getting the funds to do it. As Herbert York put it "...it is always easier to do something a second time, even if the only thing known from the first time is that it can be done." This is bad for the U.S. for two reasons. First, other nations could bypass KKV development, an area where the U.S. has a substantial lead (roughly 15 years). Instead, enemy nations could go directly to laser ASAT development, where the U.S. would have less of a lead. Second, the U.S. military is likely to remain very dependent on its satellites, probably more dependent than any other military. We will have the most to lose if it becomes possible to destroy all satellites in orbit. That day will be brought closer if the U.S. initiates a laser ASAT research program.

If we choose not to invest in such research, it is less probable that a ground-based

---

41 One minor drawback to laser ASATs is that one doesn't know for sure when a satellite is dead. It is difficult to tell if a melted satellite is dead, or simply playing dead. With a KKV, the break up of the satellite into fragments is a more visible event.
42 York, p. 33.
laser ASAT will ever be developed. Why undertake research to develop a technology that one does not want to exist? I feel that developing a technology which we do not need and which can do us significant harm is a bad idea.

But what if a hostile nation does develop an effective ground-based laser ASAT? What should the U.S. do? Under certain circumstances, it may be possible to shield satellites in SSO and GEO. This presents a dilemma because is it precisely small satellites in LEO which are the easiest to defend against KKV ASAT attack. If we are confronted with a large KKV force, the best response is to move all military functions into micro-satellites in LEO (See Section 2.4, p. 47). But if we are confronted with a certain type of ground-based laser ASAT, we want to retreat up to SSO and GEO, which is a defendable position.

If the lasers are powerful enough to destroy satellites at all altitudes, then the U.S. will have to learn to operate without them. If lasers cannot destroy shielded satellites in SSO and GEO, then the U.S. should retreat upward to these altitudes and shield them. But if an enemy nation also has KKV's, then again, the U.S. should adapt to fighting wars without its space assets.

I conclude that lasers are a high risk technology that promises to yield little more than KKV’s are known to provide today. I do not recommend that we invest effort to achieve an effect that is already available by other means.

Some might argue that high powered laser weapons will be useful for the Star Wars program. Let me digress from the ASAT focus of this dissertation for a moment to point out that many of the same factors that make laser a poor ASAT investment, also apply to BMD lasers. Lasers are still an unproven technology. Hit-to-kill BMD systems have already been developed and tested; we are more confident that they can be made to work. Lasers in the BMD role suffer from additional problems not apparent in the ASAT role. In the ASAT role, the attacker can wait for good weather to begin melting satellites. In nuclear war, the attacker chooses when to launch. A laser in the BMD role would have to be operational 24 hours a day, would have to perform perfectly, would have to shoot down many targets in a very short span of time, and might itself be under attack. Thus, it seems unlikely that we will need
ground-based lasers for ASATs, and that the chances that they will be practical in a BMD role seem even more remote.

Finally, it is worth the cost to harden all satellites against low powered laser attacks. Satellites should withstand 2 to 10 W/sq-cm before failing, and sensitive sensors should be protected from laser attack. The U.S. is already doing this. The latest generation of DSP early warning satellites, for example, now have protective lens systems which prevent high intensity light from damaging their sensors. The exact cost of these improvements is classified, but I assume that compared to the support systems and the sensors themselves, the costs of protective lenses or lens covers is minimal.

Next, I examine the utility of nuclear weapons as ASATs.

### 2.8 Nuclear Weapons

From the purely technical viewpoint, nuclear weapons make good ASATs. A dozen weapons could disable every unshielded man-made object in space. This is because nuclear weapons have an enormous lethal radius (tens of thousands of kilometers) against unshielded satellites. In fact, it is often argued that a major drawback to nuclear ASATs is that a potential attacker would destroy his own satellites as well as his opponent’s.

However, if a target satellite is modestly hardened, the lethal radius of a one megaton blast drops to 500 kilometers. This hardening adds 3-4% to the cost of the satellite (See Section 9.6, p. 266). One nuclear weapon is required to kill each hardened satellite. Even so, nuclear ASATs are still more capable than kinetic kill vehicles. Decoys are not going to be helpful unless they are far from the target, defensive maneuvers must be more radical to be effective, and a precise impact homing vehicle technology is not required.

Despite their physical advantages, nuclear weapons have serious drawbacks. Politically, there are obstacles to the use of nuclear weapons. The Outer Space Treaty prohibits the stationing of nuclear weapons in space. The Partial Test Ban Treaty
prohibits the testing of nuclear weapons in space. Use of nuclear weapons for ASAT purposes during a war between two nuclear powers might be interpreted as foreshadowing a further escalation to nuclear warfare. See Section 3.2 (p. 72) for further discussion of these points. Nuclear weapons make poor ASATs from a cost viewpoint as well. Nuclear weapons, even for a super power like the U.S., cost twice the $1 million estimated cost for a KKV. They are also roughly 100 times heavier than the new KKVs being developed. This increases the cost of launching the nuclear ASAT by roughly a factor of 20 compared to the KKV. And for smaller nuclear powers, the costs of nuclear devices may be so large that they are unlikely to be used merely as ASATs.

Another factor to consider when dealing with small nuclear powers is that their nuclear weapons may be so large or delicate that they cannot be boosted into space by rocket. That is, a nuclear power does not by definition have a nuclear ASAT capability.

On the other hand, if a nuclear power has gotten nuclear unit costs down to the millions of dollars, and does not have the KKV ASAT technology, then nuclear weapons do become the cheapest form of available ASAT.

Even so, nuclear weapons are not cheap, costing $2 million even when mass produced (see Section 9.6.1, p. 9.6.1). From a monetary viewpoint, nuclear ASATs only make sense if: one, KKV ASATs are unavailable; two, the political cost of using nuclear weapons in space are acceptable; and three, there are only low numbers of expensive satellites to destroy. If a defender has hundreds, even thousands of micro-satellites in orbit, destroying each one with a nuclear weapon would be very cost-ineffective.

2.9 Summary

In examining the nature of space warfare, I have argued that Lasers and nuclear weapons are not practical methods for destroying satellites. The weapon of choice is the pop-up KKV ASAT—provided one has the ability to produce it.
For defense, expensive large satellites in LEO are the most vulnerable and cannot
defensively maneuver or use decoys. Expensive satellites in GEO and SSO are less
vulnerable because they can defensively maneuver and utilize decoys effectively. With
many decoys, and in a crisis, the costs become roughly the same. But if the attacker
can afford to be slow in destroying the satellites, the advantage shifts back to the
attacker.

The best defensive tactic is to adopt micro-satellites for military space missions.
They shift the cost advantage to the defender. However, micro-satellites are probably
not a suitable solution for reconnaissance missions.

A gun launcher can be effective in increasing this defender micro-satellite advan-
tage by a factor of two, even if the attacker also has a gun launcher. As for satellites
in SSO and GEO, a gun launcher monopoly will help the offensive cost advantage by
a factor of two.

In the next chapter, I discuss in detail the military space policy I summarized in
Chapter 1.
Chapter 3

Future Threats and How to Meet Them

In this chapter I discuss the future threat to the U.S. in general and U.S. satellites in particular. I also expand the recommendations made in Chapter 1. In the first section I discuss policies that should be implemented now. In the second section I discuss policies that might be needed and the circumstances that would require them.

3.1 Future U.S. Conflicts

As the early 1990's have so dramatically illustrated, the world does change. With the collapse of the Soviet Union, the forces arrayed against the U.S. have been dramatically reduced. Does this mean that the future will be pacific? Perhaps, but it could also open a new era of global conflict and struggle. In this section I briefly survey some potential causes of war. The point is that U.S. military forces may be sent into action more often in the future than in the past, and that U.S. military forces will require military space systems to support them. Those readers already convinced of this can skip to the next section, 3.2.

Conflict between nations can be triggered by a scarcity of resources. For example, it seems likely that the U.S. will fight to defend its access to world oil supplies. The recent Gulf War is an example of this.
Global environment changes could add to the list of scarce resources and become a source of international conflict. Large scale disruption of local climates, and therefore food supplies could lead to starvation, migration, and invasion.\textsuperscript{1} If the U.S. grain supply were sufficiently disrupted that it could no longer feed itself, access to world food supplies would join the list of U.S. vital interests.

Civil wars between ethnic groups appears to be on the rise. As the Red Army has dissolved, long-standing ethnic hatreds in Eastern Europe, the Balkans, and Central Asia have re-emerged. Civil wars can become international wars when a nation comes to the aid of one side. The break up of Yugoslavia has demonstrated how these civil conflicts can spread and involve other nations. Yugoslavia may serve as an example to other ethnically divided societies by demonstrating the terrible costs of resorting to arms. But it may also inspire dominant ethnic groups in other nations to emulate the fairly successful Serbian method of "ethnic cleansing." The U.S. could become involved in policing such civil wars and defending minority ethnic groups.

It appears that conflict with a major power in the near future is very unlikely. I think the most probable scenario is massive civil unrest in Russia, China, or India, resulting in an expansionist regime coming to power. Such a regime would have large military resources and many directions in which to expand. The U.S., assuming the role of global policeman, might oppose any such expansion, perhaps by coming to the defense of invaded nations.

Residual commitments from the Cold War also still exist. Should North Korea invade South Korea, the U.S. would be called upon to defend its ally. This threat however, continues to decline as the South Korean economy grows. Some have argued that South Korea is already able to defend itself against the North without

\textsuperscript{1}The current water supply system running from Turkey, through Syria to Iraq is an example of a potential environmental war. A local drought might lead the downstream powers to destroy dams of the upstream powers to ensure adequate water supplies for their people. A similar situation exists in the republic of Uzbekistan (formerly part of the U.S.S.R.). Massive irrigation along two rivers has reduced the volume of the Aral Sea by 60% since 1960. Dry sea bed dust is blown across irrigated land, gradually salting it. Expanded irrigation upstream in the republics of Turkmenia and Tajikistan is reducing available water to those in Uzbekistan. Farmers in Uzbekistan are taking more water from those downstream in Kazakhstan. 40% of the population in the region is under 18 years old. This means that population demands on the environment will be larger in the future. See "A way of life evaporates," \textit{The Economist}, September 21st, 1991, p. 59.
U.S. participation. Of course, if North Korea remains hostile and develops nuclear weapons, then the situation changes. Perhaps the U.S. would conduct an air strike to destroy nuclear facilities, as the Israelis did to Iraq—Although post Gulf War investigations have demonstrated the limited effectiveness of an air campaign against nuclear weapons development. Alternatively, South Korea or the U.S. might consider a ground invasion to eradicate nuclear facilities.²

The Gulf War suggests that the U.S. might engage in military operations to deny other nations access to nuclear weapons. However, the U.S. did not initiate the war with Iraq for non-proliferation reasons. It is not certain that non-proliferation alone is sufficient to start a war.

The U.S. could be called upon to fight wars anywhere in the world. The Middle East remains a likely place for future conflict because of its unique combination of political instability, nuclear aspirations, U.S. allies, and large oil reserves. Much depends on the U.S. self image. If it adopts the role of a global police force, using violent means to punish aggressors and prevent nuclear proliferation everywhere, future wars are very likely. On the other hand, if the U.S. moves toward isolationism, vital interests would need to be threatened to involve the U.S., reducing the likelihood of war. But others would suggest that isolation increases the chances of another world war. U.S. foreign policy has traditionally been somewhere between these two extremes.

Summarizing, we see that the exact nature of future U.S. wars is highly uncertain. While the Cold War is ending, we cannot be certain that the frequency of U.S. wars will decline. Some causes of war are declining, but new causes of conflict seem to be emerging to replace them. It is possible that looking back, we may come to think of the Cold War era as comparatively pacific.

²South Korea's position on this is clear: "In private, the South Koreans make it clear that they will no sooner allow the North to build a bomb than Israel would allow Iraq to. The South's defense minister, Lee Jong Koo, went so far last spring as to broach the idea of a pre-emptive strike." From The Economist, "Spreading the new world order," November 16th, 1991, p. 40.
3.1.1 Insurance and Uncertainty

The main point of this section is that the likelihood of war in the future is unknown. John Mueller has argued that war is becoming unfashionable.3 Cites the disappearance of duelling and slavery as analogous former universal practices which have become obsolete. As the nations of the world change their attitudes, war will not be considered as a policy option. It will become "ubrationaly unthinkable." Carl Kaysen argues that the conclusion is correct, but that there are strong economic and political forces which are making war obsolete.4 Kaysen claims that there is no profit in the occupation of foreign territories. Occupied nations remain hostile, denying the aggressor effective access to the nations population skills. In the long run, the costs of occupation exceed the benefits. Kaysen also argues that all resources, including oil, are better acquired by trade than by force of arms.

These arguments are certainly encouraging, but one should not assume that wars, even major wars, will not occur in the future. My position is that we don't know if the end of the post Cold War era will continue to be relatively peaceful or bring more war. Mueller states that most powers learned the unprofitability of war during World War I, but that Adolf Hitler started World War II singlehandedly.5 If this is the case, couldn't another Hitler start another world war? Mueller argues that liberal democracies tend not to fight with each other. But Russia and China remain the second and third most powerful military forces on the planet, and they are not liberal democracies.

Kaysen's argument that there is no long term profit in war is not an argument that wars will not occur. For example, a mugger is about to attack you. As a defense, you point out to the mugger that his long term income would be maximized if he gives up crime, enrolls in school, and gets a job. I suspect that you will be unable to convince him not to take your wallet.

Some nations may only be interested in short term gain, or may be willing to take

5Meuller, pp. 64-71.
risks to drastically improve their position. Certainly, putting missile into Cuba was a highly risky way of drastically increasing the Soviet Union’s strategic position. This was a gamble Khruschev was willing to take. Mueller claims that Japan’s decision to attack the U.S. was not rational. Japan had not yet learned the futility of war and saw attack as the only option. Admiral Yamamoto’s caution that Japan would lose a long war with the U.S. was ignored. But Mueller fails to note that Yamamoto was a skilled gambler. Japan was choosing between certain defeat (acquiescing to U.S. demands in China in return for oil) or the chance of total victory in the Western Pacific (the U.S., lacking a fleet and worried about Germany, allows Japan to keep its colonial acquisitions plus its newly acquired oil sources in the Pacific).

I agree that current economic forces argue against war, and that most rich nations now feel this way. However, that is not insurance that some military power will disagree in the future. Ideally, police forces exist not to enforce unpopular decisions on everyone, but to punish the few who disagree with commonly held rules of behavior. If everyone broke the law at every opportunity, no police force would be large enough to enforce the law. The international community lacks such a police force, and so we must be prepared to defend our interests ourselves.

In the past, we could plan to fight the particular forces in particular places. War with the Warsaw Pact in Europe was the dominant scenario. Now, we no longer have a specific threat to use as a planning tool. While diminishing threats are good for the U.S. and the world as a whole, it makes military planning more difficult. Given this uncertainty, we must structure our forces to be flexible and to anticipate a number of contingencies. We must buy capability for the sake of capability, because we don’t know exactly what, if any, the threat will be in the future.

Because military space systems, like most expensive military systems, can take 5 to 15 years to develop, decisions about the future must be made now, without the benefit of knowing what kind of world we will face in the 21st century.

The question of how much money should be spent on the military versus domestic programs or the deficit (which seems to be of more importance today) is beyond the

---

scope of my dissertation. Tension will always exist between the uncertain military needs of the future known civilian needs of today. However, I have tried to incorporate this tension into my policy recommendations in the following way: on the one hand, this dissertation determines how to maximize the survivability of U.S. military space resources when confronting a range of threats; on the other hand it minimizes costs and postpones large expenditures until necessary. In other words, this military space policy is an insurance policy against a war in space in the future, but I have tried to keep the costs of this policy low. It is a low cost insurance policy to defend large, expensive space assets. Space assets support the military, which itself is an insurance policy to defend the U.S. interests in the event of war.

In the next section, I turn to specific threats of war in space.

3.2 Threats to the U.S.

In this section I examine the possible use of ASAT systems. I consider the probabilities of a range of space threats the U.S. might face, both today and in the future, both offensive and defensive.

Today, there are very few nations that can destroy a satellite in orbit. Space warfare is a rich nation's game. Few nations today have the technological capability to both build and launch satellites. These are the U.S., Russia, possibly Kazakhstan,\(^7\) China, Japan, England, France, Italy, Germany, India, Israel, and possibly Australia.\(^8\) It takes a lot of effort just to put a target into space, let alone attack one. The financial and technological thresholds to space are very high.

The thresholds to offensive space warfare are even higher. Any power with nuclear weapons and the missiles to launch them into LEO has an ASAT system. But as we will see, any nation intending to use nuclear weapons in space faces serious obstacles. Only the super powers (the U.S. and the former U.S.S.R.) have built and tested ASAT

\(^7\)Two of the three launch sites of the former U.S.S.R. are in Russia. The third lies in Kazak territory (See Joftus, Joseph P. and Charles Teixeira "Launch Systems" in Wertz, p. 617.). Whether Kazakhstan will build a space program from this is uncertain.

\(^8\)NASA operates a launch site in Australia.
weapons of any type. With the continuing disintegration of the Soviet Union, one might expect that only the U.S. has this capability today.

**Future Uncertainty**

Today it *seems* that the possibility of war is declining. Most technologically sophisticated powers are U.S. allies. The Soviet Union continues to disintegrate. One could make the argument that nations like Iraq, without nuclear weapons, are the biggest threat the U.S. is going to have to face for decades.

But we don’t know. If all U.S. wars of the future involve nations like Grenada, Panama, and Iraq, it would seem that we have little to worry about. But the future international environment is very uncertain. For most of the Cold War, the U.S. had a sizable opponent, the Soviet Union, whose forces were the primary basis for U.S. military planning. Now, we are forced to plan on the basis of unknown forces in unknown places. This is not such a terrible thing as long as one remembers that one cannot defend the U.S. against all threats. But it is equally irresponsible to ignore unlikely threats simply because they are unlikely. These days, I am surprised by unlikely events every time I pick up the newspaper.

In this section I examine alternative war scenarios to determine the threat to U.S. military space systems and, where needed, suggest an appropriate response in each case.

**3.2.1 Offensive Options**

I begin with a discussion of U.S. offensive options. Although the entry costs to space are very high, several nations have space assets that could be of assistance to their military forces on Earth, providing navigation, communication, and reconnaissance. Let’s take each of these in turn.

**Navigation:** As I state in Chapter 8, the U.S. will probably retain a monopoly on satellite navigation. If so, the U.S. can simply encode GPS data, effectively denying it to the enemy for military purposes. If a foreign GPS system (like Russia’s Glonass system, which is currently in jeopardy) is built, then the U.S. would need a high
altitude ASAT if it wished to destroy it.

**Communications:** A major enemy power is likely to have many communications satellites while some third world nations may only have one or two. If enemy communication satellites are few, and of simple design, then the simplest way to neutralize them is to use a U.S. communications satellite as a jammer. By moving next to the opponent's satellite, the U.S. can jam the downlink. This requires time on the order of days to move the satellite. The target satellite can only be jammed if it lacks both frequency hopping capability and electronic beam focusing capability. Also, the U.S. would have to do without this satellite just as our own needs for military communications increased.

If the opponent has as many sophisticated communications satellites as the U.S. does, then the opponent's communications satellites become just as much a threat to our communications as ours do to theirs. Under these circumstances, a GEO-capable ASAT would be needed if the U.S. wished to destroy them. As I noted earlier, the U.S. already has all the components needed for a GEO-capable ASAT, it just needs to put them together and to test them.

**Reconnaissance:** Currently China, France, and Russia have reconnaissance satellites of one form or another. In order to destroy enemy reconnaissance satellites we will need a kinetic kill ASAT like the MHV system now in storage.

Thus, if a significant enemy space threat emerged, the U.S. would need ASAT's at both low and high altitudes if it wished to destroy them.

If the opponent has invested in microsat communication reconnaissance or navigation technology, then the cost advantages of KKV ASATs would be reduced or even eliminated. New launch technologies such as a gun launcher might provide a factor of two improvement in cost to destroy a micro-satellite, but only if the cost is as low as projected (See Section 9.5, p. 259). Gun launchers would be less helpful to the defender.

The U.S. could also use its nuclear weapons as an ASAT system. But it would encounter difficulties which are explained in Section 3.2.3 below. For these reasons, and because KKV's are available to the U.S., the U.S. should not even consider use
of nuclear weapons as an ASAT system.

We have seen that the U.S. already has all the components needed to destroy enemy satellites at any altitude. LEO-capable ASATs already are in storage. Emergency encoding of GPS data will prevent enemy use of GPS signals. Testing of a GEO-capable version can wait until such a threat emerges.

3.2.2 Jamming

I now turn to defensive options, that is, how to protect U.S. space systems from being neutralized. I begin with a discussion of existing threats.

The one threat most nations can pose to U.S. space assets is uplink jamming (see Section 3.3.3, p. 89). In fact, Space Command officials were quite relieved that Iraq never attempted to jam satellite transmission from the Kuwait Theater of Operations during the Gulf War.⁹ However, as the U.S. continues to build jamming resistance into its new communications satellites, this threat should diminish with time.

3.2.3 Nuclear Weapons in Space

Another space threat which exists today are the world's nuclear weapons, which make effective ASATs (see Section 2.8 p. 64).

The History of Nuclear vs Conventional ASATs

Only the U.S. and the former U.S.S.R. have developed ASAT weapons systems. The U.S. deployed, and then cancelled, two separate nuclear armed ASAT systems (see Section 10.6 on ASAT history, p. 347). The Russian nuclear-tipped ABM system defending Moscow could function as an ASAT system. Russia has also tested a radar-sensing co-orbital ASAT system. Tests of an IR-sensing system failed. Only the U.S. has the IR homing system necessary for high speed impact, the Miniature Homing Vehicle (MHV) LEO ASAT. Now under development in the U.S., is the

lighter Kinetic Kill Vehicle (KKV). Israel is developing a BMD interceptor called the Arrow, with substantial U.S. help. This system could evolve into a LEO ASAT.

The historical trend has been that a nation will develop nuclear weapons before it undertakes conventional ASAT development. Nuclear weapons represent a much larger payoff in terms of prestige and power than ASATs. This may change in the future (more on this later) but this history had produced two effects: first, the only foreign powers that are developing KKV’s are those with nuclear weapons; and second, many nations have only nuclear weapons to use as ASATs.

**Nuclear Threat to Unshielded Satellites**

If the U.S. satellite population were unshielded, then nuclear ASATs would be very destructive. When using nuclear weapons against unshielded targets, the attacker can be tens of thousands of kilometers from the target and still destroy it (see Section 9.6 p. 266). If half the U.S. satellite reconnaissance could be wiped out with a single device, then use of a nuclear ASAT might become an attractive possibility to an attacker. As I discuss below, a minor power is unlikely to have a booster capable of reaching SSO or GEO. But a nuclear ASAT in LEO could kill unshielded targets in SSO. A nuclear ASAT reaching SSO altitude could kill unshielded targets in GEO. Thus, having unshielded targets reduces the altitude and guidance requirements of a nuclear ASAT booster.

**Foreign Nuclear Wars**

If unshielded, U.S. satellites could also fall victim to nuclear detonations in space which were not intended to destroy them. If Russia were to end up in a war with another former Soviet republic with nuclear weapons, or China, demonstration nuclear detonations in space would be a real possibility. Also, the nation at war with Russia might want to disable Russian military satellites and would only have nuclear weapons to use as ASATs. Without nuclear hardening, U.S. military satellites could become collateral casualties of such a war. Commercial satellite owners, who might resist hardening their satellites, could become collateral casualties as well.
But if the U.S. shields its satellites from long range nuclear effects things change: First, the attacker must use at least one nuclear ASAT to kill each satellite instead of getting area kills. Second, the booster used to launch the ASAT must actually reach GEO to kill GEO satellites instead of reaching only to SSO. Third, the attacker must have the satellite tracking and booster navigation capabilities to get her ASAT within 500 km of the target. Finally, U.S. military satellites are much less likely to become collateral casualties.

Next I turn to the problems of using nuclear ASATs against shielded satellites. I consider two cases: first, an emerging nuclear power which has recently acquired nuclear weapons and has a limited inventory; and second, an established nuclear power with hundreds or thousands of warheads as well as the missile systems to deliver them anywhere in the world.

Emerging Nuclear Powers

Here I discuss the emerging nuclear powers, once they have emerged and their ability to use nuclear weapons as ASATs. There are many nations that probably have or are trying to develop nuclear weapons. These include Israel, Pakistan, South Africa, Iraq, and North Korea. But this discussion examines nations that have recently succeeded in developing nuclear weapons. This reduces the set of nations most likely to develop nuclear ASATs to Israel and India. Any minor power with nuclear weapons is likely to have a small number of them. These weapons are costly to develop and produce. Thus, they are unlikely to be used rashly.

Further, the weapons available to a small nuclear power might not be the small compact warheads the U.S. has developed after almost 50 years of production. Newly developed nuclear weapons simply may be too big, too fragile, or too heavy for available missiles to lift into space.

As we have seen in Section 2.8 (p. 64), nuclear weapons are potent ASAT weapons. But it is difficult to imagine circumstances under which a small nation at war with the U.S. would use them. Conditions would have to be desperate: imagine U.S. forces invading a minor nuclear power to depose its leaders. One could imagine its leaders
using nuclear weapons to destroy U.S. forces and perhaps salvage their situation. But they would risk nuclear retaliation by the U.S.

Nuclear ASAT use against U.S. satellites, however, would not necessarily result in U.S. use of nuclear weapons. No U.S. personnel, only U.S. equipment, would be destroyed by the nuclear weapon. The U.S. would probably not have any space targets to retaliate against, nor would the loss of any space assets constitute a substantial deterrent for a small nation. In the Gulf War, the U.S. was very concerned about the use of chemical weapons, but did not plan to retaliate if Iraq used them. This suggests that the U.S. would not necessarily respond to a nuclear ASAT with nuclear weapons.

A national leader might want to attack U.S. LEO satellites with nuclear weapons as a demonstration of nuclear capability and the will to use nuclear weapons. Attacking satellites would kill no one, and fallout would not be a serious problem. Under these circumstances, the large low orbiting reconnaissance satellites would make good targets. These extremely expensive satellites are few in number and in very low orbits.

Under these circumstances, the outcome depends on the booster size and the nuclear weapons used. Certainly, reconnaissance satellites would become vulnerable. Half a dozen nuclear ASATs would be sufficient to destroy all U.S. reconnaissance satellites in LEO. Satellites in SSO and GEO would be much harder targets to reach. SSO and GEO capable boosters are very sophisticated technologies not found in emerging nuclear powers. It is very unlikely that SSO and GEO satellites would be endangered.

Summarizing, I conclude that the use of nuclear ASATs by an emerging nuclear power would only occur under extreme circumstances. Individual nuclear weapons would be particularly valuable to an emerging nuclear power. Nuclear weapons might not be deliverable by missile. And if deliverable, will almost certainly not be capable of reaching SSO and GEO altitudes. The implication is LEO reconnaissance satellites might become vulnerable to nuclear ASAT attack from small nuclear powers.

Next I turn to the special problems faced by established nuclear powers when contemplating the use of nuclear ASATs.
Major Nuclear Powers

It seems unlikely that the U.S. would engage in direct conflict with another established nuclear power. Certainly a war in which either side was fighting for its national existence would seem likely to end in a nuclear exchange. For this reason, one would expect that any such war would be fought under highly contained circumstances. But the risks of such a theoretically containable war are considerable. One could argue that a conventional war between the superpowers in Europe, Korea, the Middle East, or Vietnam could have been fought under containable circumstances, and yet both superpowers went to great lengths to avoid any direct conflict.

But if such a war were to break out, nuclear weapons would almost certainly not be used as ASATs. Because nuclear weapons would exist on both sides, use of a nuclear device, even in space, would represent a dangerous escalation. Either side might feel the need to preempt once the nuclear threshold was crossed. Both sides would therefore work very hard to prevent any use of nuclear weapons, despite the tactical advantages their use might present.

One could argue that the losing side might want to conduct a demonstration nuclear detonation to indicate that it was becoming desperate and that it was considering resorting to widespread use of nuclear weapons to defend itself. Such a nation would want to use a nuclear weapon in a place that would provide a tactical advantage, where loss of life and fallout would be minimal, and where no nuclear weapons already existed (lest the attack be perceived as the beginning of a counter force attack). Under these circumstances, LEO would be a likely place to use a nuclear weapon. No human casualties would result. It would provide some tactical gain, be highly visible, and would not destroy any nuclear weapons.

Assuming then that the initial use of nuclear weapons would be for demonstration purposes, few—probably only one—would be used. Targets would be satellites in LEO because attacking GEO targets would be threatening. Early warning satellites are typically located in high orbit either in GEO or in Molnya orbits. If nuclear weapons began going off at these altitudes, the demonstratee might conclude that this was an attempt to blind him to a full scale nuclear attack. Thus, for demonstration purposes,
targets would almost certainly be confined to LEO.

Under these circumstances, the war would be coming to a close. The demonstration use of a nuclear weapon would be designed to signal desperation and a desire to cease hostilities. One would hope that both sides would be sobered by the demonstration and would arrange to negotiate terms. If the demonstration failed, the likely outcome would be either capitulation or a large scale nuclear exchange. In all cases, the conventional military uses of space would be at an end; the war would end or enter a non-conventional phase.

Summarizing, I conclude that nuclear ASATs are almost certainly not going to be used in any conflict between nuclear capable powers because of the escalation problems involve. The one exception to this is a demonstration use, in which case one ASAT will probably be used against a LEO satellite. Satellites in GEO would enjoy a special immunity because early warning satellites are deployed there.

The only scenario I can imagine that would produce a large number of nuclear ASAT attacks is rather extreme. The enemy nation must have a nuclear weapons production capacity sufficient that nuclear weapons can be launched into space, and that use of a dozen nuclear weapons would not drastically reduce the stockpile or represent a high cost. It must have sufficient missile technology to make repeated attack into LEO, but cannot have sufficient missile capabilities to threaten the U.S. homeland with nuclear attack. Under these conditions we could imagine large numbers of U.S. LEO satellites being destroyed. Those in SSO and GEO would remain safe, since any power with GEO capable boosters is also capable of putting nuclear weapons onto U.S. soil.

But I believe that the chances that such a nation would ever meet all these conditions and get into a war with the U.S. while these conditions still applied are very remote.

3.2.4 KKV’s

In this section I evaluate the chances of an enemy of the U.S. developing KKV ASATs. I also discuss which U.S. satellites will become vulnerable first and suitable counter
Early Warning of Foreign KKV Development

Today, only Russia and the U.S. have conventional ASATs. The U.S. has KKV ASATs, the Russian ASAT is co-orbital. From the U.S. perspective, currently there is no KKV ASAT threat. However, any rich, industrialized, major power could develop an ASAT system, which could constitute a threat to U.S. space assets. As noted at the beginning of this chapter, and further discussed in Section 9.8 (p. 275), we can expect at least three years warning of a foreign ASAT in development and perhaps as much as ten years. Based on U.S. ASAT development history, we expect the time between a first visible test of a KKV ASAT and its deployment to be about three years. We should be able to detect any test in orbit. The test would involve a sub-orbital launch (probably a pop-up attack on one of their own satellites) which would be detected by our DSP early warning satellites. NORAD tracks all sizable man-made object in LEO with radar. In the event of a successful test, a target satellite would disappear from the LEO satellite inventory (or be converted into a set of smaller fragments).

How Poor Nations Might Acquire KKV’s

In the future, KKV’s may be developed by other nations for reasons other than threatening U.S. space assets. One possible scenario is that a nation with a large weapons manufacturing industry, like Brazil, or a highly technological nation which has consciously avoided nuclear weapons, such as Canada, might develop an ASAT system. One could imagine such a nation working on an air defense or BMD system, which could evolve into an ASAT system. Certainly the Iran/Iraq War and the Gulf War demonstrated the power of ballistic missiles to threaten urban populations. It is possible that many nations will now want to acquire BMD systems.

It is also possible that a small nation might purchase or be given the necessary technology from larger, richer, more technologically capable nations. Who would have thought before the Falklands war that British ships would have to face French Exocet missiles? Who would have thought before the Afghan war that the Afghans
would be using U.S. Stinger anti-aircraft missiles? Who would have thought before the Gulf War that the U.S. would be facing a soviet style armor force equipped with Swedish artillery, with superior range than our own? I cite these examples to point out that soldiers of technologically unsophisticated nations can effectively use technologically sophisticated weapons. I also wish to point out that systems built by one's technologically sophisticated allies can end up in the hands of one's enemy.

**LEO is More Vulnerable than SSO or GEO**

KKV ASATs could eliminate the U.S. overhead reconnaissance capability. It is important to differentiate now between ASATs capable of hitting targets in LEO, and those capable of hitting satellites in SSO and GEO. I argue that the latter is much less likely than the former. Missiles of various types are currently being sold to third world nations. These missiles, when combined with air defense radars and a KKV, could represent a LEO ASAT threat. But to reach SSO and GEO is another matter entirely. Only major powers (the U.S., the former U.S.S.R., France's Arianespace,\(^{10}\) Japan, and China) possess, or will soon possess, the large rockets and the satellite tracking facilities needed to attack targets at these altitudes. GEO-capable boosters are expensive, require extensive launch facilities, and provide commercial revenues. Like jet aircraft manufacture, launch services are viewed by most of these nations as a key technology for competing economically. Launch services are a core element in any rich nation's industrial policy (except for the U.S. which has no civilian industrial policy). For these reasons they are not being sold or given to Third World nations.

In addition to the booster, attacking satellites in SSO or GEO requires a satellite tracking ability. Radar is not sufficient to detect satellites at these altitudes. If the satellite is a communications or navigation satellite, the attacker has the advantage that the satellite broadcasts information and thus betrays its location. If the satellite is not transmitting, it must be tracked optically. If the satellite is not transmitting

---

\(^{10}\)Arianespace is a consortium made up of the following partners: France, Germany, Belgium, Italy, the U.K., Switzerland, Spain, the Netherlands, Sweden, Denmark, and Ireland. France has a controlling 58.46%. See *Interavia Space Directory 1989-90* p. 302.
and is painted black, a space-based IR system is required to track it.

Further, unless the target is a GEO satellite visible from the attacking country, these tracking facilities must be placed far from the attacking nation. Attacking GEO requires global tracking or space-based tracking.

In contrast, targets in LEO are much easier to see and attack. A large radar is sufficient to track satellites in LEO and the physics of LEO ensure that all satellites pass within 250 km of the radar every twelve hours. Getting to LEO is much easier, sub-orbital pop-up trajectories are all that is required, reducing necessary rocket size significantly.

LEO satellites—and U.S. reconnaissance satellites in particular—will be the first to become vulnerable to KKV's. If I knew that the U.S. was going to encounter enemy KKV's, I would recommend that the U.S. abandon continued development of large, expensive reconnaissance satellites and work on a terrestrial system.

Thus, the threat to be more concerned about is a LEO KKV ASAT, not a SSO/GEO KKV ASAT. Given an operational enemy LEO KKV force, the low level reconnaissance satellites are sitting ducks (see Section 2.2, p. 39). In this scenario, a U.S. ASAT would be of little help. It cannot defend U.S. satellites, and the minor power is unlikely to have any military space assets it could attack. Here a program of reconnaissance aircraft and GEO-based weather satellites would seem a prudent backup.

**Counter Measures to KKV's**

If faced with an enemy KKV, the U.S. might want to take some defensive measures. Decoys will be ineffective in defending LEO targets. Investment in decoys for satellites in SSO and GEO would be helpful, they would make destroying U.S. satellites more difficult and would be effective in defending against limited numbers of KKV's. But the cost advantages would still lie with the attacker if KKV's were produced in large numbers. The only way to deal effectively with a large ASAT threat is to use micro-satellites. These are the only systems that offer an effective cost exchange ratio. A gun launcher might also provide substantial savings (as much as a factor of 100) in
launch costs. Construction of a space gun and destruction of any opponent's gun launcher would further increase the overall cost advantage by a factor of two, if the gun launcher costs are as low as predicted (See Section 9.5, p. 259).

Responses to LEO Vulnerability

Unfortunately, good imaging resolution currently requires large optics, which cannot be miniaturized. The diffraction limit determines the best resolution of a telescope. This limit is based on physical principles. It may be possible to bypass this physical limit and create smaller optics with equivalent resolution, but it seems very unlikely. Reconnaissance satellite will always be both necessarily large and in LEO, and therefore vulnerable.

A more reasonable course of action given the uncertain threat and the certain costs of changing U.S. reconnaissance satellite platforms is for the U.S. to retain an aircraft reconnaissance capability. If U.S. satellites are attacked by a minor nuclear power, the U.S. is likely to have control of the air, allowing aircraft overflights of important areas. AWACS, JSTARS, and reconnaissance equipped fighters are likely to remain in the force for some time to come. These aircraft were not built to be a backup to space-based reconnaissance capabilities, but the vulnerability of reconnaissance satellites argues for retaining them.

3.2.5 Summary

We have seen from the cases listed that space threats can range from none to large numbers of ASATs, from low to high altitude, and from nuclear to conventional. Several trends are clear.

First, jamming resistance and nuclear hardening should be built into all U.S. satellites. Jamming resistance prevents any nation with a satellite antenna from jamming uplinks. Nuclear hardening prevents any nuclear power from disabling the entire U.S. satellite population with a handful of nuclear ASATs.

Second, the most common ASAT currently available is the nuclear weapon. Any nation with nuclear weapons and some missile capability (such as India) has the
makings of a LEO ASAT.

Third, there are strong political incentives not to use nuclear weapon in space. Nuclear powers, when fighting the U.S. are unlikely to initiate use of nuclear weapons for tactical advantage. Rather, we can expect them to be used only for demonstration purposes at the close of hostilities.

Fourth, small nuclear nations that cannot attack the U.S. homeland, but that can reach LEO may be free from these constraints and may attack U.S. LEO satellites with nuclear weapons.

Fifth, LEO targets will be threatened before those in SSO or GEO come under nuclear or KKV attack. The lack of GEO boosters in all but the most technologically sophisticated of nations means that SSO and GEO satellites are less likely to be threatened.

Finally, we have seen that the nature of a threat depends on technology and numbers more than on national size and nuclear capability. National size can affect the chances of a nation developing certain technologies, but it is the technical capability that determines the threat. Iraq with a KKV is much more of a threat to U.S. space assets than China is today. Nuclear weapons are unlikely to be used as ASATs, while non-nuclear ASATs require significant technological ability. With the exception of U.S. allies such as Israel, any ASAT development program (or BMD program) will be significant because it will produce technology that threatens U.S. space assets — technology which is currently very rare. Thus, the threat today remains minimal, but any ASAT/BMD development program in a potentially hostile nation should be taken very seriously.

Next I discuss response to threats which might emerge in the future.

3.3 A Realistic U.S. Military Space Policy: What to Do Now

Now it is time to put all the pieces together into a single U.S. military space policy. I consider threats and present appropriate responses. Not all the threats postulated
will come to pass. In fact, it is possible that none of the threats postulated will come to pass. Given this fact, it would be foolish to begin spending large amounts of money on mostly defensive projects which we will, in all probability, never need. Any realistic military space policy must choose among options, always aware of the costs involved.

My strategy in formulating such a policy is three-fold: first, buy the cheap options as a prudent hedge against future threats; second, defer all expensive options; but third, determine at what point we should exercise expensive options. In this section, I discuss measures we should undertake today. This corresponds to Threat Level One from the Executive Summary in Chapter 1. The recommendations can be grouped into three categories: defensive, offensive, and environmental. I begin with defensive measures.

3.3.1 Hardening Military Satellites Against Nuclear Attack

Military satellites should be hardened against nuclear detonation and low power lasers. This prevents U.S. assets from being taken out by “cheap shots.” This option will only add roughly 3% to the cost of satellite systems. Hardening of satellites against long range nuclear effects means paying a small cost to substantially increase the chances of satellite survival. Adding such a cost to U.S. military systems will not be difficult. Military systems are supposed to be rugged and survivable. The military in general is intended to deal with irregular, improbable, hostile events, and 3% is a modest price to pay.

An additional low cost measure is to harden sensors against low power laser attack. These measures are difficult to cost. They involve the installation of protective shutters or special lenses in front of the imaging instruments. In comparison to the sensors, optics, and positioning equipment, I believe that the cost of these covers is minimal. The necessary design innovations have already been incorporated into some U.S. military satellite designs. It seems a worthwhile effort to continue.
3.3.2 Hardening Commercial Satellites Against Nuclear Attack

Commercial communications satellites are an important addition to military communications satellites. In the early days of the Gulf War mobilization, 50% of long haul communications went via commercial carriers.\textsuperscript{11} It took several days to reposition a DSCS satellite, after which no commercial satellites were needed.

As a substantial user of commercial communication satellites, the Department of Defense should encourage commercial communications service providers to harden against nuclear attack. It could preferentially subscribe to those satellites with hardening. Or it could provide monies to pay for the additional cost of satellite hardening just as the Air Force currently pays airlines for the cost of keeping their planes capable of providing heavy airlift when needed. IntelSat and Inmarsat are the international commercial corporations responsible for most commercial satellite communication and navigation. As a large voting member of both of these organizations, the U.S. can attempt to influence these organizations’ decisions toward more robust, hardened satellites.

One could argue that in the course of a war, an emerging nuclear power might detonate a nuclear weapon in space. I outlined a possible scenario for this in Section 3.2. Without hardening, commercial GEO satellites could be unintended victims of long range effects. If they were thought to be carrying U.S. military traffic during a war, then they could also become intended targets. The corporations could lose all of their space assets as a side effect of a war. For a modest percentage increase in cost, these satellites could be protected.

Unfortunately, 3% higher cost means less profit. A 3% cost increase is not a trivial sum in the commercial world, which intends to make a profit. The chances of a nuclear weapon being detonated in space may seem remote in the commercial world, especially when weighed against the certain costs of hardening.

The history of getting commercial carriers to harden their systems against nuclear

\textsuperscript{11}Cannan, James W. "A Watershed in Space" \textit{Air Force Magazine} August 1991, p. 34.
attack is not encouraging. AT&T hardened their long distance communication systems for the SAC which was using them to carry air defense and attack information. But they only did so because they wanted to placate the U.S. government. AT&T was worried about being broken up under anti-trust laws and saw serving the U.S. military as a way of demonstrating the usefulness of their monopoly.\textsuperscript{12} U.S. military traffic did not hold any commercial value for AT&T,\textsuperscript{13} they were primarily interested in civilian traffic. Because they were a monopoly, they had incentives to harden systems to avoid anti-trust actions, and because they were a monopoly they were able to pass the costs onto their customers without worry of competition.\textsuperscript{14}

Today's commercial satellite communications providers are much less likely to harden their systems than AT&T was. They have been a monopoly up to now, but new competitors are beginning to emerge in the satellite business. This means that the carrier that refuses to harden its systems will have a cost advantage over other carriers. In addition, the entire commercial satellite communications business is threatened by optical fiber cables. Once in place, these cables can carry vast amounts of information over global distances. Cable is less flexible than satellite communication, so the market will not disappear entirely, but for fixed long haul communications (such as U.S. to Europe) it seems that optical cable is the long distance medium of the future. Currently cable costs are higher than satellite costs, but as optical cable technology improves, the balance will shift toward cable. For all these reasons, satellite systems designers will be pressed to minimize costs to compete with cable as long as possible. They will be uninterested in adding an additional 3% overhead to satisfy the paranoid fears of the U.S. military, only one of many customers.

On the other hand, as optical cables take over the market in fixed long haul communication, commercial satellites will be forced to focus on those users who need

\textsuperscript{12}Bruce-Briggs, B. The Shield of Faith, Simon and Schuster Inc., New York, 1988, p. 26. In the end, SAC developed its own communications system and AT&T was broken up.


\textsuperscript{14}Congress became upset with the charges AT&T was billing to the military for its long distance services and forced the phone company to reduce its bills. But of course these costs were also passed onto civilian users. See Bruce-Briggs, p. 87.
flexible global long haul communications. That is, communication customers who
don't know where they will need communications from day to day. This reduces
the customer base from all telephone users, to the military, emergency services, and
television news coverage. This inevitable reduction in customer base may make the
commercial satellite community more responsive to military needs in the future. But
commercial satellite operators believe that this is a long time off. Even if it does
happen, it is also possible that non-military customers will continue to dominate the
market, in which case military requests for hardness are less likely to be honored.

3.3.3 Uplink Jamming

Jamming resistance, in the form of adaptive nulling or frequency hopping, should be
built into all future U.S. satellites. For details of jamming see Section 9.7, p. 271.
Without uplink jamming resistance, communication satellites could not do their job.

The costs of jamming resistance appear to be substantial. We can compare two
U.S. military communications satellites: DSCS and Milstar. A Milstar 2 satellite
(with adaptive nulling) on orbit will cost about $675 million (see Table 2.1 p. 50)
and will have a transmission capacity of 48.5 Megabits/sec.\textsuperscript{15} That comes to $13.9
for each bit/sec capacity.

A DSCS III satellite (with some jamming resistance but without adaptive nulling)
on orbit will cost $152 million\textsuperscript{16} and can be expected to transmit 188 Megabits/sec.\textsuperscript{17}
That comes to $0.81 for each bit/sec capacity. Thus, the increased cost per bit/sec
for Milstar's adaptive nulling is roughly a factor of 17 more than for DSCS without
adaptive nulling.

As for getting commercial carriers to do the same, it can be argued that adding

\textsuperscript{15}Dornheim, Michael A. "Milstar 2 Brings New Program Role" Aviation Week & Space Technology
November, 16th, 1992, pp. 63-64. The older Milstar satellites had a capacity of only 0.6 Mbits/sec,
but were expected to successfully receive and transmit during a nuclear war. The Milstar 2 satellite,
has almost 100 times the capacity, but is not expected to work while a nuclear war is in progress.

\textsuperscript{16}See Table 2.1 p. 50.

\textsuperscript{17}Total DSCS III bandwidth is 375 MHz, assuming the systems uses FSK modulation (common in
military systems) capacity will be about half of this bandwidth or 187.5 Megabits/sec. See Davies,
Richard S. in Wertz, Table 13-8, p. 457 and Table 13-8, p. 467.
jamming resistance would be in these organizations' best interests. The current satellite communications system depends upon all nations to respect the frequency allocations of the International Telecommunications Union (ITU). The system currently depends on all nations' cooperation in abiding by the ITU's decisions. But any nation could begin jamming satellites if it felt alienated from the current international structure.\textsuperscript{18} Jamming resistance would be a good insurance policy against rogue nations.

Certainly the U.S. should continue to design jamming resistance into its communications satellites, either in the form of adaptive nulling or frequency hopping. Getting commercial carriers to do the same is probably impossible because of the costs involved. No carrier is going to increase its costs by a factor of 17 just to retain military traffic (unless, as I stated above, the military becomes its most important customer).

However, recent technological innovations in GEO antenna design may provide commercial carriers with some jamming resistance. Modern commercial communication satellites come with electronically steerable antennas. This, in effect, gives them the ability to transmit (and also receive) to limited portions of their FOV. Thus, a commercial satellite might not be able to receive information near a hostile jammer, but it might be able to ignore a jammer outside its area of focus.

\section{Decoys and Impact Sensors}

A relatively cheap defensive option against some forms of ASAT attack is the use of decoys and impact sensors. A decoy basically consists of a balloon and an inflation mechanism that can be jetisoned from the satellite on warning on an impending attack. The decoy should be able to defend against both KKV's and nuclear ASAT's. The decoy should be able to separate itself from the satellite by a distance of at least 550 km within 45 minutes of launch. This allows the decoys to be sufficiently separated from the satellite and each other so that a single nuclear ASAT cannot kill

more than one decoy or hardened target. This package could easily be reduced to a few kilograms in weight (see Section 9.4, p. 255). The advantage is that these simple, cheap, and lightweight decoys can dramatically increase the chances of survival for a satellite under attack by a few ASATs.

But a key to this decoy strategy is the ability to detect an attack. DSP sensors can do this, but not always. By transitioning from LEO to GEO over either pole, an attacker can avoid DSP detection by using a very roundabout attack profile (see Section 9.4, p. 255). It is also possible to station an ASAT in GEO posing as a non-offensive satellite, and then move it to kill another satellite in GEO.

In either of these scenarios, the impact sensors play a role. These are detectors (already in use on some U.S. military satellites) that detect impact with foreign objects. The idea is that even if the satellite is disabled, the impact sensors can report that the satellite has been attacked, rather than simply failing for some undetermined reason. If the ASAT is nuclear, it will be abundantly clear that the satellite was attacked. Thus, even if the ASAT launch is not detected, the defender will know that he is under attack when the first satellite is destroyed. The advantage of impact detection is that the defender can command all other satellites to launch some or all of their decoys. Unless the attacker can kill all targets within the short defender reaction time, then the other satellites can be defended.

Thus, the decoys and impact sensors work together to hedge against the possibility that an ASAT attack is not detected. And a very low cost. This is a much cheaper solution than building a LWIR space-based scanning system to track all man made objects in space, which would run roughly $700 million to build and launch.

While decoys and impact sensors are not now required on satellites in SSO and GEO, we should equip satellites in LEO with them. These satellites will be the first to become vulnerable to ASAT attack of any type. Decoys and impact sensors will provide some defense against pop-up KKV's and nuclear ASATs, and will provide substantial defense against co-orbital ASATs.

The logic is to equip LEO satellites to hedge against a sudden and unexpected re-appearance of the Russian co-orbital ASAT. If it is re-deployed, then we equip
satellites in SSO and GEO to anticipate the development of a GEO-capable co-orbital ASAT.

3.3.5 The Global Positioning System

The U.S. should offer the commercial GPS user community GPS signals without Selective Availability. However, the U.S. should retain the right to encode all GPS signals during wartime. In addition, we should arrange for Inmarsat and the FAA to be given the necessary codes to continue to offer Differential GPS navigation services to authorized aircraft and ships. See Chapter 8 for a more detailed discussion the GPS system and of these issues.

3.3.6 Subsidizing Motorola’s Iridium Project

Iridium is a proposed satellite communications project using 77 satellites in LEO to implement a global cellular phone network. Its sponsor, the Motorola Corporation, is currently looking for investment partners and hopes to be operational by 1997. For more details, see Section 3.4.3, p.109. Of all the current schemes for LEO-based communications satellites, Iridium is the most decentralized. It is also the only project that can transmit globally without resorting to existing long distance telephone communications lines.\(^\text{19}\)

Subsidizing the Iridium project can provide a lot of leverage for the dollars spent. By helping to initiate Iridium the U.S. spends very little and gets a lot. The help would probably be in the form of a long term usage contract. One of Iridium’s biggest problems is convincing investors that there are customers for this service.\(^\text{20}\) The investors, encouraged by a committed customer, would provide the $3.5 billion dollars to design, build, and launch the system. Motorola would do the innovative work of creating a highly flexible, decentralized communication system that is available to the U.S. military. It might even be possible to get Motorola to build nuclear hardness

\(^{19}\) *Aviation Week & Space Technology*, May 18th, pp. 60-81.

\(^{20}\) Goodwin, Bill “Pie in the sky?” *The Engineer* January 30th, 1992, p. 25.
into the satellite’s design.

For a very small cost, the U.S. gets a highly innovative system designed and built along lines it might someday need to build itself. It gets a prototype built and running without having to pay the costs of development.

One way to hedge against future threats is to reduce the development time of a micro-satellite communications system. Helping the Iridium system get off the ground seems a good way of creating a working prototype at low cost.

If the U.S. ever does need to build a military micro-satellite communications system, it would employ smaller, cheaper satellites in greater numbers than the Iridium system. But Iridium represents a first step in this direction, and would provide valuable field experience with a totally new type of communications network. Iridium is not cost competitive with KKV ASATs, but it is much more cost competitive than Milstar. Iridium would present 77 targets instead of Milstar’s three. Based on a 5 year expected satellite lifespan, Iridium would replace its satellites, on average, once every 23 days. Thus, Iridium satellite production and launch would be very frequent, providing a limited replacement capability while under attack. Milstar satellites take years to design and build; once the on-orbit satellites were destroyed, replacement under attack would be impossible.

3.3.7 Gun Launcher Development

A gun launcher is predicted to reduce launch costs by two orders of magnitude. But even if these costs are as low as predicted, we have seen (See Table 2.1, p. 50) that the total system cost of putting a satellite into orbit or launching a KKV ASAT to kill a satellite falls only by a factor of two at most. This is because LEO satellite costs and LEO KKV ASAT costs are more than the launch costs for either system.

Thus, when combined with microsats, this technology could tip the offense/defense cost balance in either direction by a factor of two for one side or the other, if one side obtains a space gun monopoly over its enemy.

The gun launcher will be effective in wartime only if the enemy's gun does not exist or is silenced. If the enemy has a gun launcher with similar launch costs, odds are
he will also be building micro-satellite networks. In order to destroy these, the U.S.
gun launcher must be kept operational both to replace U.S. satellite losses to enemy
ASATs, and to launch U.S. ASATs to destroy enemy networks. But there could be
hundreds of microsat targets to kill. It will take time to kill these (depending on
the technology, a gun launcher could be limited to two firings per day). Thus, once
a micro-satellite network is in place, the U.S. can depend on it well into the war.
But the same is true of enemy micro-satellite networks. The survival of either side’s
satellite population might come to depend on how fast either side’s gun can fire and
whether or not those launches are devoted to ASATs or micro-satellite replacements.

There are also commercial implications to building a gun launcher. The global
launch market could be radically altered if the U.S. opened up a gun to commercial
launches. This could hurt rocket development world-wide, and spur other nations to
build guns of their own.

If the U.S. were to build a gun launcher, it is likely that other nations would
follow suit. This is because a gun launcher would have commercial applications for
launching satellites into LEO. In fact, the gun launcher becomes cheaper the more it
is used because fixed capital costs can be amortized over more launches. Given that
the European satellite launch consortium Ariane was created precisely to compete
with the U.S.’s launch capability for commercial launches, it is likely that Europe and
perhaps Japan would respond by building gun launchers of their own.

I would recommend continued research on gun launchers, at an estimated cost
of $4 million per year.21 If gun launchers prove to be as cheap as their proponents
claim, they could provide an additional factor of two cost advantage for a KKV
ASAT system that was attacking a enemy micro-satellite network. It would also be

21 Currently there are three projects running which together spend slightly less than $4 million per
year on average. The coil guns project has spent $7 million over 4 years, or $1.75 million/year (see
Henderson, Breck “Sandia Researchers Test Coil Guns For Use in Orbiting Small Payloads” Aviation
Week & Space Technology May 7th, 1990, pp. 88-89). The ram cannon has spend $2 million over
three years, or $0.67 million/year (see Henderson, Breck “Ram Accelerator Demonstrates Potential
for Hypervelocity Research, Light Launch” Aviation Week & Space Technology September 30th,
1991, pp. 50-51). The gas gun project has spent $4 million over 3 years, or $1.33 million/year
(see Henderson, Breck “World’s Largest Light Gas Gun Nears Completion” Aviation Week & Space
Technology August 10th, 1992, pp. 57-58). This totals to $3.75 million/year, I rounded up to $4
million/year.
storage to provide a stop gap force for such a contingency. Keeping the existing
ASAT systems in storage and in good repair seems to be a good idea. The MHVs
in storage should be replaced by KKV's once they too have been tested. If, by some
miracle, the Star Wars program is halted and KKV's are never tested, then MHV's
should be sufficient to provide the U.S. with an on-the-shelf LEO offensive capability.

3.3.9 Ground-Based Lasers

Theoretically, ground-based lasers have the potential to clear the heavens of all man-
made objects, or rather to melt them into useless globules of metal. But it also seems
that the technological obstacles to achieving this capability are very formidable.

If ground-based laser systems are created, those satellites in LEO will become
vulnerable first. If the technology runs up against certain limits (see Section 2.7, p.
59), satellites in SSO and GEO might survive with Tungsten shielding. But it is also
possible that all satellites will become vulnerable.

The U.S. is much more dependent on its military space assets than any other
nation. It seems unlikely that it will ever face a nation with more military space
assets. Therefore, the U.S. would have the most to lose and the least to gain should
ground-based laser ASATs became a reality. For these reasons, I argue that the U.S.
should halt further research into high power lasers now.

Some will argue that we need to conduct research because others might be doing
it and we need to be current if a breakthrough occurs. The fear is that another
power might develop a new laser technology capable of great power, many orders of
magnitude higher than current experimental systems. I dislike this argument and find
it unpersuasive. The U.S. has little to gain and much to lose from a laser ASAT. High
powered laser programs may provide incentives for other nations to do similar research
and could create a technological arms race into dangerous and destabilizing programs.
If the laser research is successful, it shows that it can be done and encourages other
nations to follow suit. Finally, an effective ground-based laser ASAT would increase
the U.S.'s ability to destroy satellite, but the U.S. already has more offensive capability
than it needs. Lasers would add little of value.
3.3.10 Downlink Jamming

Other elements of space policy depend on the type of threat that emerges. Currently no other nation has offensive space systems (except for Russia) so we have no real problems. If an enemy nation had one to two communication satellites in GEO, if might be useful to neutralize them. A sacrifice of a U.S. communications satellite might be a reasonable cost for jamming the enemy’s entire space communications network. To create an effective GEO jammer, we would need a robust military communications satellite that would be able to broadcast over a wide variety of frequencies.

Building a reliable GEO jamming system does present some technical difficulties. If the target satellite is directional, it can focus all its beam energy to a particular point, drowning out the jammer, which would then have to spread its energy over the entire satellite FOV. Perhaps the jammer could be made to sense the target satellite’s beam position. It would also have to change frequencies if the target satellite changed frequency.

But this idea is really a stop gap measure for very limited target sets. If efficiently neutralizing large numbers of enemy GEO satellites is the goal, then KKV’s are the answer. The idea of using a satellite to jam an enemy satellite is an offensive option available to the U.S. if an enemy power has one or two communications satellites. Rather than undertake a GEO ASAT testing and development program, we could use this option instead. But as soon as the enemy satellite population appears to be increasing beyond one or two, then a GEO ASAT program is needed if we wish to destroy them.

Now I move to a discussion of environmental issues.

3.3.11 The Space Environment

We must consider all threats to U.S. military assets, even unintended ones. A man-made threat is orbital debris. Every year the chances of hitting significant chunks of man-made debris in Earth orbit increases.
Orbital debris, especially in GEO should be addressed with an international agreement requiring all satellite launchers to provide for a de-orbiting procedure. This involves moving to a super-synchronous orbit with two small rocket burns at the end of the satellite’s useful life. The cost would be 10 m/sec in thrust, 5 to 10 kg of fuel for an average GEO satellite mass, or 1 to 2 months of lifetime for a typical satellite.\textsuperscript{23}

Other procedures to minimize debris from discarded rocket stages also need to be adopted. Almost empty fuel tanks should be vented to prevent explosions. Although LEO is self-cleansing because of atmospheric drag, should a gun launcher be developed, the sudden increase in launched mass could present problems unless special measures are undertaken to minimize debris from the rocket used to circularize\textsuperscript{24} the projectile’s orbit. See Table 6.1 (p. 174) for orbital lifetimes.

But these measures will only postpone the problem of debris at higher orbits, not solve them. As we have learned here on Earth, one cannot simply throw things out without concern as to where they end up. Existing debris is already a serious hazard in GEO. The real solution is to clean up the existing GEO space trash. In the very long term, we will need an orbital janitor that will pick up large pieces of debris and push them into super-synchronous orbit.

Why move debris upward (into super-synchronous orbit) instead of downward (into sub-synchronous orbit)? Super-synchronous orbit is better for two reasons. First, for a given acceleration, one gets more physical separation moving into higher orbits then into lower orbits. Second, almost no space traffic moves beyond GEO, while all GEO satellite boosters must pass though the sub-synchronous belt to reach GEO.

The janitor might be a robotic system equipped with solar powered ion engines. These engines produce much more total thrust than a chemical rocket, but they are heavy and accelerate very slowly. They are not currently used for space applications.


\textsuperscript{24}This is the process whereby an elliptical orbit is converted into a circular one. The satellite waits until it is at its apogee (highest point) and to add enough additional orbital velocity to sustain a circular orbit at that altitude.
because they take a long time to get anywhere.

The janitor would be launched into GEO to intercept dead satellites. Once attached to a satellite, it would gradually spiral up to super-synchronous orbit. Releasing the satellite the janitor would begin to spiral down to GEO for another cargo. The released satellite would continue in super-synchronous orbit, essentially forever.

A janitor project would not be cheap. Perhaps the satellite launching community could be persuaded to contribute to an environmental fund, based on each member's contribution to the GEO debris problem.

The one type of system that would not be retrievable is the Soviet nuclear powered radar satellites in LEO. The reactors in these systems are dense enough to survive re-entry. In fact, one satellite failed to boost into a higher parking orbit in the late 1970's and scattered radio active debris over Canada. In other words, these satellites are too hazardous to return to Earth and lifting them out of LEO to super-synchronous orbit would be very expensive. For this reason the Russians should be dissuaded from launching any more of these reactors into space. A possible exception to this ban would be reactors that are to leave the Earth's gravitational field. Inter-planetary missions for example.

As for those reactors currently in ULEO, perhaps the solution is to boost them out of Earth's gravity well despite the expense. Solar powered ion engines or perhaps solar sails could be used to gradually lift these systems into Solar orbit and perhaps eventually into the Sun itself. One advantage of a solar powered system is that if you are willing to wait long enough, you can go anywhere in the solar system. Of course, these janitors would probably not return since they would take years to perform their missions.

Now the reader might think that this scheme of moving junk into super-synchronous orbit is simply dumping from one place to another, and the reader would be correct. But super-synchronous orbit is a great dumping ground: it's a very big place, moving things around is very easy once you are there, and there is no space traffic except for the occasional moon mission or inter-planetary probe. It will solve the problem for awhile.
To solve the problem permanently I propose two alternative very long term solution. The first option is to use the solar-powered ion engine driven janitor system to de-orbit the debris. Once the satellite is low enough to be affected by atmospheric drag, the janitor can release the satellite and begin spiralling upward to GEO or super-synchronous orbit to get another payload. The satellite will burn up in the atmosphere (Russian radar satellites excepted). However, this solution would require a much more robust janitor device. The total acceleration required to move down to LEO from GEO (4,700 m/s)\(^{25}\) is much more than that required to move from GEO to a safe super-synchronous orbit (10 m/s). Also, the janitor would have to generate enough thrust to overcome the atmospheric drag which claims the jetisoned satellites.

If this proves technologically too difficult or expensive, then I propose the following alternative. Use another class of janitor system, using solar sails for propulsion, to move junk from super-synchronous orbit into the sun. By pointing their sails at a 45 degree angle to the sun, the sail will accelerate away from the sun and slow its solar orbital angular velocity. This should result in an highly eccentric elliptical orbit that intersects the surface of the sun. Once this orbit is entered, the sail can collapse and be destroyed along with its payload.

3.4 A Realistic U.S. Military Space Policy: What to do in the Future

In this section, I discuss actions that may be necessary in the future. None of the following measures need be undertaken at present. Rather, what follows is a list of contingencies and reactions. I list a series of space threats that might appear in the future. Each is more threatening than the last. In each case, I list a set of recommendations.

Just as some of the previous section's recommendations were designed to hedge against each future threats, some recommendations at each threat level are intended to

\(^{25}\)Weisel, p. 90.
guard against greater future threats. The threats I consider in this section correspond to threat levels two through five from the Executive Summary in Chapter 1. The threat levels are: two, the co-orbital ASAT; three, a limited number of KKV ASATs; four, a large number of KKV ASATs; and five, a ground-based laser ASAT.

3.4.1 The Co-Orbital ASAT Threat

Here I consider responses to a slightly increased threat, namely, a re-vitalized, hostile Russia with a LEO co-orbital ASAT. In fact, this is the only foreign conventional ASAT system ever built. If the Russian military space program unravels as the Soviet Union had unraveled, this threat may never re-emerge.

However, should a militant Russia or some sort of hostile confederation emerge, co-orbital ASAT in hand, our LEO reconnaissance satellite would again be vulnerable. This is why (in the previous section) I recommended adding decoys and impact sensors to LEO satellites. This is a low cost counter measure to the co-orbital ASAT threat. Decoys will make it much more difficult to destroy our reconnaissance satellites. Additionally, I recommended maintaining reconnaissance aircraft as a backup.

Given the possibility that an enemy might develop a GEO co-orbital ASAT, the U.S. should invest in decoys and impact sensors for satellites in SSO and GEO.

One might also be tempted to build a GEO LWIR scanning system to detect attacks coming from LEO to GEO. But this system would be costly. Assuming the LWIR satellites with the same number of detectors (although of a different type) would cost roughly the same as a DSP early warning satellite, we can expect the two satellites to cost $250 million each,26 plus roughly $100 million to launch each of them (See Section 6.5, p. 185). Total cost: $700 million. This is an expensive option just to deal with a clunky 2,500 kg Soviet-style ASAT that might be upgraded to attack things in GEO.

I would argue at this stage that existing DSP early warning satellite coverage would be sufficient to provide attack warning to satellites in SSO and GEO. As I

---

note in Section 9.3 (p. 241), DSP will pick up GTO launches in LEO provided that they do not occur over the poles. This alternative route to attack GEO involves a 90 degree plane change once the co-orbital ASAT reaches GEO altitude. This imposes a further factor of 4 increase in total rocket mass. Thus, putting a 2,500 kg ASAT into GEO without being detected by DSP would require a rocket capable of putting 10,000 kg into GEO with a normal trajectory. The only operational booster capable of putting this much mass up at once is the Energia booster\(^{27}\) (which is so large it could lift two ASATs). The point is that the costs of putting that much mass into GEO ($250 million, See Table 2.1 p. 50) via such a inefficient route, precludes multiple undetected attacks. The necessary rockets to conduct these attacks would be so massive that concealing the ASAT launches as routine launches would be very difficult. It is possible that these boosters could disappear from LEO without being noticed, but the odds are low.

It seems to be that DSP does provide sufficient coverage to provide attack warning. In the one case where attack warning is not provided, the costs for the attacker are so high that it seems unlikely that it will ever be made.

Against a low closing velocity co-orbital ASAT, satellites in GEO and SSO can hold their own, because they can get sufficient warning. Recall that satellite decoys have a similar advantage to that which nuclear RV decoys enjoy. Until the war happens, no attacker really knows how many there are or what their optical and IR properties are. Thus, the attacker never knows what kind of decoy he is going to face.

It might be possible for the attacker to send ASATs to force the defender to deploy her decoys, examine the decoys deployed from Earth, and then re-design the sensors on the ASATs to differentiate the decoys from the targets. But doing a re-design over the course of a war seems to be highly unlikely. After all, it is the sensor that is one of the most technologically challenging part of the ASAT, re-designing and testing it in time to make a difference in a war seems very improbable.

For those who claim that a war could drag on for years, and therefore that the

---

attacker might have time to redesign the ASATs, I would claim that the defender then has time to react to the threat as well. The defender could launch simple satellites with nothing but a guidance system and decoys to defend the satellites. These decoys could have different properties to further confuse the attacker’s ASATs.

A U.S. ASAT system would not deter the Russians from using their ASAT system. The Soviet Union was much less dependent upon its military satellites than we were and are. Soviet military commitments were primarily in regions adjacent to their homeland, global communications, navigation, and reconnaissance were not essential to the conduct of its primary military missions. Presumably the same would hold true for a future Russian force. They are also less able to use the military opportunities that satellites present. Certainly, a U.S. ASAT would have no deterrence value, as others have argued in the past, because loss of satellite capability would mean much more to the U.S. than to Russia.

Of course, the U.S. might want an offensive system to attack Russian satellites in the event of war. But as I noted in Section 1.1.4, p. 29, the U.S. already has plenty of offensive systems and is likely to have more in the future as a result of BMD development. A Russian ASAT threat does not, in and of itself, increase the need for U.S. offensive systems.

### 3.4.2 A Limited KKV ASAT Threat

Next I consider the consequences of an enemy initiating development of a hit-to-kill ASAT system similar to the U.S. MHV or KKV ASATs. If we detect the R&D effort when it begins, then I estimate that we have 10 years to respond before the ASAT system is operational. If we detect the effort when the first on-orbit tests are begun, then I estimate that we have three years before the ASAT system is operational.

**KKV Development**

In deciding what actions to take, we must consider the timelines of both the U.S. and any hostile nation. Current U.S. military satellite systems can take 10 to 15 years to design and launch, and then stay on orbit for another 10 years (See Section 9.8.2,
p. 278). That is a very large time horizon to deal with. If we knew that five years from now our entire satellite system would be attacked by large numbers of KKV’s, we would abandon large military satellites and begin a micro-satellite program to replace all existing functions.

Fortunately, we also know that it takes a long time to develop KKV ASAT system. The U.S. took 10 years to develop the MHV, and it looks like it’s going to take at least another 9 years to develop the smaller, lighter KKV interceptor (See Section 9.8.4, p. 279). Of course, we may not be certain that a nation is working on such a system until the first test in space. Even then, the U.S. history implies that we will have at least 3 years warning between the first test and operational status.

Even if we assume the worst—that as soon as a high-tech power emerges that intends to do us harm they immediately undertake KKV research—we still have 10 years to react, and such a power has not yet emerged. It is possible that nations, such as Israel, will develop BMD systems that will provide the required components of an ASAT system, and that they will sell these components to our enemies. But this seems a very unlikely scenario. I am willing to risk that such an event does not happen and to trust that we will get sufficient warning of an enemy ASAT system to allow us to reach and begin building microsatellites.

An additional factor working for the U.S. is the fact that wars do not happen as soon as space military assets become vulnerable. If a hostile power emerges, and begins an aggressive ASAT campaign, even if the ASAT system becomes operational, the war may never happen or it may be some time before a war begins. This lag may provide additional reaction time.

How easy would it be to develop this kind of technology? Admittedly, a 25 kg homing vehicle would reflect U.S. technology that is over 15 years old. But the probability of this threat emerging seems low because the technology required is rare. Some nations could almost certainly develop the necessary equipment. Israel—thanks largely to U.S. funding—is developing the Arrow BMD system, which contains much of the technology required. Nations in Europe and Japan could probably also develop such a system if they were willing to invest the money. All the nations that could most
easily produce this system are U.S. allies. A hostile Russia might be able to build such a system, but its previous efforts to build IR sensing ASATs were unsuccessful and were abandoned. 28

Of course, arms sales are common means of weapons technology transfer. One point of view is that nations will want BMD systems in the aftermath of the Gulf War, and that defense contractors in many rich nations with falling defense budgets might see a large potential market and initiate development without government funds. BMD technology can be used to build ASATs as well.

It is possible that Israel or another U.S. ally could sell homing vehicles to other nations hostile to the U.S. However, Israel would have much to lose if ASAT/BMD technology were to proliferate. In fact, Israel and all the nuclear powers would find their missile-based nuclear forces weakened if BMD systems became widespread. U.S. allies in Europe are developing military satellites of their own for reconnaissance. Selling BMD systems to potentially hostile nations would threaten their military satellite programs as well.

Will the U.S. ever have to face this threat? Probably not. Currently the chances of such a threat every emerging seem rather remote. But one can think of scenarios in which the U.S. will someday have to face this threat. Fortunately, it seems that the U.S. will have ample time to react to a KKV ASAT threat because it will take years to emerge. See Section 3.5 (p. 111 for a complete timeline chart for all threat levels. It would be useful to know what the U.S. should do under such circumstances. This is our next topic.

The Kinetic ASAT Threat

Once the enemy KKV ASAT system is fielded, the LEO reconnaissance satellites become undefendable. Ascent times for a pop-up KKV ASAT to LEO are so short that there is not time to react and deploy decoys. The costs of building and launching a LEO reconnaissance satellite are roughly 500 times higher than the costs of killing

it. There is no way to continue to maintain satellite reconnaissance under these conditions.

The navigation and communications satellites in SSO and GEO will be harder to attack. Higher altitude attacks require more sophisticated launchers. The U.S. has had a working MHV for many years now, and has gone on to develop a KKV, but none of these systems can reach targets above LEO. Thus, we can expect a LEO capable enemy KKV or MHV to appear before a SSO or GEO capable one.

Further, a high altitude gives more time to react to an attack and deploy decoys. But a key element of this system is being able to see the attacker coming. The DSP system will not be adequate to detect all KKV attacks, because the KKV’s are so light, taking a polar ascent trajectory to GEO is now much more practical. And because the KKV has a high closing velocity, it doesn’t need to make the 90 degree plane change required of the co-orbital ASAT.

Thus, in order to anticipate these high altitude defense needs, once a GEO capable hostile nation begins developing KKVs, or once a KKV capable hostile nation begins developing a GEO booster, I recommend that hundreds of decoys and a few impact sensors be added to each SSO and GEO satellite designs, and that we begin building a two GEO satellite LWIR scanning system to detect KKV attacks at higher altitudes.

Decoy Costs

How much will these decoys cost? The cost of these decoys comes from the cost of getting their mass into orbit. A DSCS satellite is 1150 kg with launch costs of $54,000/kg. A hundred decoys weighing 3 kg each would cost roughly $16 million dollars per satellite, or roughly 10% of total satellite plus launch costs. Milstar launch costs are $35,000/kg, and it weighs 4,500 kg. 100 15 kg decoys would cost $54 million, or roughly 5% of satellite plus launch costs. Thus, 100 decoys seems to add 5%-10% to on-orbit satellite cost.
The Costs of Reconnaissance Micro-Satellites

One theme I have held to in developing a space policy is not to undertake expensive policies until one seems forced to do so. Until now, I have avoided recommending conversion to micro-satellites because would probably be more expensive than current systems.

In the area of reconnaissance, the costs of moving to micro-satellites are difficult to estimate. If seems very unlikely that high resolution reconnaissance may not be possible with a collection of small satellites. The optics require a large mirror (order 1 m) to resolve images. But image processing does hold out some hope. Currently computers enhance images blurred by thermal eddies in the atmosphere. This technology might be able to combine several low-resolution images into a single high-resolution one. It seems likely that this new method, even if possible, will be much more expensive than existing KH-11 imaging systems. Also, unlike micro-satellite communication or navigation, reconnaissance micro-satellites cannot tumble. They must have a precision pointing capability in order to look at specific locations on Earth. This means that the basic micro satellite platform will also be more expensive than than used to provide communication or navigation services.

Thus, it is unlikely that LEO reconnaissance satellites can be defended or converted to a micro-satellite constellation. Given this threat, we should assume that we will lose these assets at the outset of any war that owns KKV's. Reconnaissance aircraft should be retained to provide a backup for satellite systems.

3.4.3 Numerous KKV ASAT Threat

This next level of threat is difficult to quantify. Basically, it attempts to draw a line between dozens of enemy GEO-capable KKV ASATs and thousands of them. Once the enemy is capable of fielding thousands of KKV's, things change. One could imagine the attacker, rather than sending hundreds of KKV's to destroy a satellite, investing in an optical or multi-spectral capable ASAT system to differentiate decoys from the actual satellite. Or perhaps installing radio emission homing devices on
KKVs and waiting for a particular target to start transmitting.

In other words, once the attacker is able to invest in more complex SSO and GEO satellite kill systems, the value of decoys begins to decline. All the attacker needs to do is find something that differentiates the decoy from the satellite and send his KKVs against the satellite.

When this becomes true depends on how many KKVs the enemy has, how high the enemy’s boosters can go, and the technological capability of the attacking nation. At some point, the owner of large numerically small constellations of satellites in SSO and GEO will be overwhelmed by attacker offensive advantages. Under these circumstances, the only option for the defense is to use micro-satellites in LEO which can compete with pop-up KKV ASATs on a cost competitive basis.

The Costs of Micro-Satellites

In the area of navigation, as with reconnaissance micro-satellites, the costs are difficult to guess. A navigation satellite consists, essentially, of an atomic clock in a known orbit that constantly broadcasts the time and its position. The atomic clocks used in the GPS satellites cost $100,000 each, to the clock will not radically increase the cost of a micro-satellite which typically cost hundreds of thousands of dollars. The existing constellation requires only 20 satellites (plus 4 spares) with four atomic clocks in each for redundancy. A micro-satellite system would require many more satellites because of their limited FOV, but only one atomic clock would be needed in each satellites. But overall, the cost of a global micro-satellite navigation network would be higher than the existing GPS system. How much higher, I don’t know.

The best understood case is that of communication satellites. The Iridium system will be capable of funneling a total of 680 Mbps through 15-20 ground stations at a cost of $3.5 billion. That comes to a cost of $5.15/bps. A single DSCS military satel-

---

30Phone conversation with John Windolph, Iridium Corporation, April 27th, 1992.
lite will transmit 188 Mbps\textsuperscript{32} and costs $152 million.\textsuperscript{33} That comes to $0.81/bps. The Iridium system has the advantages of much greater flexibility, increased survivability, graceful degradation, and global coverage that the DSCS does not, but the DSCS is roughly a factor 6 times cheaper than Iridium based on raw data transmission.

A micro-satellite communication system that would compete effectively against KKVs would have to be even more decentralized, using smaller satellites. These systems would also probably have to use frequency hopping techniques to make them jam resistant. In other words, a military micro-satellite communications system is likely to be even more expensive per bit transmitted than the DSCS.

What this means is that we don't want to replace our GEO-based military communications systems and our SSO-based navigation systems unless or until we have to. This is also true of our reconnaissance and navigation satellites as well.

**Micro-Satellite Development and The Iridium Project**

To compete with KKVs on a cost basis, we would need large constellations of very small communication satellites and, if possible, very small reconnaissance and navigation satellites. They are difficult to destroy, and degrade gracefully under attack. They also shift the cost balance from strongly offense dominant to weakly defense dominant.

These satellites would not be individual communications links as with the current large defense communications satellites. Rather, they would be part of a network of satellites. Each satellite would talk to users under it. It would also be linked to nearby micro-satellites. Each satellite would know the position and direction of all adjacent satellites, allowing routing of messages to other ground users, perhaps circumventing heavily loaded nodes. Since adaptive nulling requires directional antennas, these micro-satellites would use frequency hopping to avoid jammers. In fact, with frequency hopping, all the satellites could use the same frequency band since

\textsuperscript{32}Total DSCS III bandwidth if 375 MHz, assuming the systems uses FSK modulation (common in military systems) capacity will be about half of this bandwidth or 187.5 Megabits/sec. See Davies, Richard S. in Wertz, Table 13-8, p. 457 and Table 13-8, p. 467.

\textsuperscript{33}See Table 2.1 p. 50.
the chances of interference are small and any occurrences would be of limited duration. Satellite communications can be made error-correcting to compensate for the occasional lost bit due to mutual interference.

In order to develop micro-satellite technology for potential future needs, the U.S. should assist the Motorola corporation’s Iridium project now. This is a program to put seventy-seven 454 kg satellites into 767 km orbits. The object is to provide worldwide cellular phone service. Perhaps the government could best assist the project by promising to become an enthusiastic customer. By offering large contracts, Motorola might be persuaded to add laser and nuclear hardening to the satellite design. This would provide a benefit to the civilian population and would move satellite designers in a direction that is militarily more desirable than packing everything into a single large spacecraft. It would also provide a backup communications system that would degrade gracefully under attack.

The Iridium system would provide a prototype for the micro-satellite system I picture. Each satellite talks with adjacent satellites and routes communications. Once the system is up and working, military micro-satellite designers (perhaps the Motorola corporation) would have a working prototype. The military system would have to be miniaturized, and hop frequencies. It would also have to deal with a larger number of nodes, and handle a greater communications load. This may seem a daunting list, but electronics get better, faster, and cheaper every year.

As I stated above, micro versions of reconnaissance satellites will probably not be possible. Precise optics may not be possible in small satellites. Navigation micro-satellites seem more feasible since atomic clocks and transmitters seem to be things that could be made very small. The one question is whether or not the orbital perturbations in LEO are as predictable as those in SSO. But if these military space missions are going to survive in the long term, these technical problems will have to be solved. As a backup, aircraft versions of these systems should be retained. We already have reconnaissance aircraft which can act as a ground-based alternative, and we should retain these aircraft in the force. As for precise navigation, a network of GPS radiating aircraft and fixed sites at known locations can provide very precise
GPS signals. While not necessary yet, we should plan for the possibility of equipping future AWACs and JSTARS aircraft with GPS emitters.

3.4.4 Lasers

Finally I come to the largest threat: ground-based lasers. If a working ground-based laser is deployed, the U.S. military will have to be prepared to fight without its space assets against any nation that manages to obtain—and successfully defend—this capability. It will be impossible to maintain any presence in space, even a micro-satellite presence, given the rate at which a high powered laser can thermally overload a satellite (a matter of seconds).

Under these circumstances, terrestrial communications, navigation, and reconnaissance will become the order of the day. Fiber optic cables might be able to provide communications needs in areas that are already wired, provided the enemy does not have a naval force capable of cutting them. Otherwise, we might see a revival of short wave radio for long distance military communications. Ground and air based GPS signal emitters could provide local theater navigation. Aircraft could provide overhead reconnaissance.

3.5 Timelines

In this section I summarize the policy recommendations by placing them all onto timeline diagrams. These timelines are shown in Figures 3-1 and 3-2, with time running along the horizontal axis from now to 15 years from now. The diagrams are divided into five components, one for each threat level. Threat Level One calls for adding decoys to LEO satellites which can be accomplished over 3.2 years.\textsuperscript{34} This is shown as a triangle, which goes from zero to 100\% over a 2.1 years, starting now. These decoys are designed to counter an operational Soviet-style co-orbital ASAT

---

\textsuperscript{34}The record KH-11 orbit lifetime is 1,175 days (3.2 years, see Burrows, p. 240 and Richelson, Jeffry "The Future of Space Reconnaissance" Scientific American January 1991, Vol. 264, Number 1, p. 39.). This means the longest it will take to replace the entire LEO population is 3.2 years.
 Threat Level One: 
Already Exists  

Response: 
Install LEO Decoys & Impact Sensors

Threat Level Two: 
Dev of Soviet-Style 
LEO Co-Orbital ASAT

Response: 
Install GEO Decoys & Impact Sensors
GEO-Capable Soviet-Style Co-Orbital ASAT

Figure 3-1: Policy Timeline, Threat Levels One and Two
Figure Notes: Dashed lines represent uncertain times. Solid boxes represent estimated project warning times. Dashed boxes represent unknown project development times. Thick arrows indicate responses called for by policy recommendations. Thin arrows indicate race conditions. Triangles are gradual changes in satellite inventory which go from zero to 100%.
Figure 3-2: Policy Timeline, Threat Levels Three, Four, and Five

Figure Notes: Dashed lines represent uncertain times. Solid boxes represent estimated project development times. Dashed boxes represent unknown project development times. Thick arrows indicate responses called for by policy recommendations. Thin arrows indicate race conditions. Triangles are gradual changes in satellite inventory which go from zero to 100%.
which is shown in Threat Level Two. Because we do know how long, if ever, it will take for this threat to emerge, it is shown as dotted line leading to a box with a question mark. We don’t know how long it will take to re-create this system so the box (representing the time needed to get the ASAT back online) is dotted. Then, sometime after the system is operational, a war might begin with this co-orbital capable nation. This is shown by the dotted line leading to the “War Begins” event. In other words, sometime in the future the ASAT system may be re-created. This recreation may take very little time and sometime after that we may get into a war with this nation.

This sets up a “Race Condition” with the LEO decoy deployment. That is, if the war versus a co-orbital capable nation occurs before these decoys are in place, some of the U.S. LEO satellite will be vulnerable.

The re-creation of an operational LEO co-orbital ASAT triggers a response, as the “Policy Trigger” arrow indicates. Upon receiving warning that a co-orbital ASAT is being made operational, the U.S. should begin adding decoys to all new GEO satellites. Complete replacement of the GEO population should take about 10 years. This deployment of decoys is racing with the nation that may decide to deploy a GEO-capable co-orbital ASAT system. I estimate that this will take at least three years and will be dependent on an operational LEO co-orbital system. Thus, the diagram for the GEO-capable co-orbital ASAT indicates that sometime after the LEO system become operational, development may begin and will require at least three years of testing (three years of warning). Sometime after that, a war may break out. Depending on how long that takes, 30% to 100% of the U.S. GEO satellite population will be protected with decoys.

Threat Level Three emerges when a hostile nation with GEO launch capability begins developing KKV’s (10 years development, with 3 years testing) or when a KKV-capable nation begins developing GEO boosters (6 to 8 years development time). This triggers installation of many decoys on GEO satellites (10 years) and construction of an LWIR space-based ASAT detection system (3 years). The race is between ASAT/booster construction and decoy deployment. The worst case for the
U.S. is if the GEO booster-capable nation develops KKV's in secret and then tests for three years and then immediately goes to war. Under these circumstances, only 30% of the U.S. GEO satellite population will be protected.

Threat Level Four is emerges when the KKV threat becomes overwhelming. I have no estimate of when this might happen. When it does happen, the U.S. should be able to deploy micro-satellites within a year. Because micro-satellite are so small and cheap, their design times are very short. Also the Iridium network (which is being designed now and will take 5 years to build) should provide a working prototype.

Finally, Threat Level Five emerges when a limited-power ground-based asat is built. I say limited-power because if the laser can destroy even shielded satellites in SSO and GEO then no response (other than to abandon military satellites) will be sufficient. If the laser is limited, however, then the U.S. will require 10 years to shield all its GEO satellites. If the laser ASAT becomes operational and the war starts before the 10 years are up, then only a percentage of the GEO satellite population will survive.

This timeline illustrates that my space policy is not without risk. Under extreme circumstances, portions of the U.S. satellite population will be vulnerable for a few years. I feel that the policy anticipates threats and defends U.S. satellites adequately, at reasonable cost. As with most military assessments, we could spend more money to reduce risk. But I feel that additional money to eliminate these risks would be wasted. If in the future we expect to get into a war with a nation that is engaged in a crash ASAT program, we might want to increase the pace of our defensive deployments, at a higher cost. But for now I feel that the pace I have recommended is sufficient.

3.6 Conclusion

Looking back on this space policy, it seems clear that the costs will probably be quite modest. On the current recommendations, only jamming resistance involves costs larger than 3% of satellite cost. Only if a threat emerges in the future can we foresee large expenditures.
But one should not conclude that because the costs are modest, the need is modest. On the contrary the need is great. At each threat level, I have anticipated further threats. This is because of the large lead times required for space systems. If our military space assets become vulnerable at a time when our terrestrial military is incapable of functioning effectively without them, then the risks we would run would be large indeed.

The military is our insurance against an unexpected hostile enemy. We pay for it to deal with things we cannot predict. It would be foolish to then ignore potential (and unexpected) threats to the space assets upon which that same military depends. If we are going to purchase insurance, let's make sure we get total coverage, especially if the additional coverage is available, with a little foresight, and at low cost.
Part II

Detailed Technical and Historical Considerations
Chapter 4

The Physics of Earth Orbit

Space is an alien environment. While the laws of physics remain the same, movement in space is very different from movement on Earth. In space there is no ground, air, or water to provide support, lift, or buoyancy; nor is there any friction, drag, or resistance. The Earth’s gravitational field determines the laws of motion of objects around it.

This chapter will provide background as well as analysis. This chapter consists of three sections: The first section describes space as a medium and compares it with land, water, and air. The second section examines the physics of Earth orbit. The third section evaluates the change in velocity ($\Delta V$) required to execute two methods of ASAT attack: co-orbit and pop-up. This last section also examines the $\Delta V$ costs of defensive maneuver to avoid intercept.

4.1 The Medium of Space

Space is a new medium. As a battleground, it presents new challenges and opportunities, just as sea and air presented new challenges and opportunities in the past. In this section we examine how space compares to other media and then illustrate how the Earth affects the space environment.
4.1.1 Land, Sea, Air, and Space

Consider how the medium of space compares to better known media: land, sea, and air. We can identify several general trends as we move from land to sea to air to space. These are:

- Manueverability decreases.

- Visibility and velocity increase.

- Geographical obstacles become less significant and natural choke points decline in number and importance.

- Cost per pound of cargo transported increases. Exception: sea transport is less costly than land transport.

- Transport via the medium becomes more precarious. That is, cargoes are more easily lost or destroyed. Greater technological sophistication is required to move within the medium.

- Control of the medium itself becomes less important. Rather, control over the craft that move through the medium becomes paramount.

Land, the dry surface of the Earth, is where the vast majority of human activity takes place. Most people spend most of their time on land and most of their material possessions and natural resources are on or beneath land. Nations are defined by the soil that they control. Dispute over land is the proximate cause of almost all wars. Land then, is the dominant medium.

Sea is the next most important medium. Almost all commerce between bodies of land occurs via water. Moving goods by sea requires a knowledge of ships and how to move them. Movement on the surface of the water is more precarious than on land. If a ship sinks, its cargo is often lost forever. If a truck tire punctures or a train derails, the cargo may be damaged, but it remains accessible.

The fragile nature of sea travel and the value of commerce to nations, make sea control an important military issue. Control of the water itself is not significant (with
the exception of oil drilling and fishing). Rather, it is control over the ships which move over the water which is significant.

Movement over water is less restricted than movement over land. Geographical obstacles are much less frequent at sea. One might think of movement over land as movement over geographical obstacles, while movement at sea is movement between geographical obstacles. Straits and canals become choke points of commerce. Controlling these tiny waters can provide effective control over vast oceans.

Visibility at sea is higher than visibility on land. At sea the curvature of the Earth is often a ship's only means of concealment. On land, the nearest ditch may suffice.

Air continues the trend established when moving from land to sea. Movement through the air requires a higher level of technological sophistication. Movement through the air is even more precarious than over water.

In addition, the costs of moving cargo per pound via the air is significantly higher than via ship. But movement through the air is significantly faster. Thus, high value per pound cargoes which are time urgent are moved via air. Such items are CEO's, tourists, and Federal Express packages. In the military world this means that paratroopers and helicopters are shipped via air, while armored divisions are not. Fighter bombers deliver munitions accurately to places where artillery cannot fire with accuracy.

As with the sea, control of the air in and of itself is not significant. Unlike the sea, however, control of the commerce that is conducted via air is not very important. Rather, control over military aircraft that deliver firepower and relay back reconnaissance is important. Movement through the air is less restricted than over land or sea. Geography presents few obstacles to modern aircraft.

Visibility in the air is also higher than at sea. As with ships at sea, in good weather the horizon represents the only real cover for aircraft. But because aircraft fly at altitudes above sea level, the effective horizon is much further away. Aircraft can fly at low altitude, using terrain as cover, but airborne radars can pick out moving aircraft from ground clutter.
**Space** continues all the trends we've identified as we move from land, to sea, to air. The costs, both technological and technical, of movement in space are sharply higher than for land sea or air. These costs force only the lightest and most valuable of commodities to be moved via space: information.

This information can have military value. Satellite photos, global military communications, and satellite navigation, provide force multipliers. The U.S. military would have been severely hampered in the Gulf War without the use of its space assets.

Thus, in space, control over space is not important, control over commerce conducted via space is not important, but control over the vehicles that relay military information is important.

Visibility in space is also better. Although there is weather in space (Solar Radiation), it does not significantly interfere with visibility. Earth itself is the only object to hide behind. But because satellites can only orbit above the atmosphere, even the lowest satellites (200 km altitude) are visible to large areas of Earth. And because satellites move over the Earth so quickly (one orbit every 1.5 to 24 hours), their visibility is effectively global in scale.

This points out another fact of space travel: poor maneuverability. Satellites move over vast distances, but changing direction is very difficult. Because orbital velocities are so great, changing direction in any significant way is almost never done.

Another trend we've identified, which is continued in space, is the precarious nature of travel within the medium. Getting into space is a very precarious business: rockets regularly fail during launch, destroying their payloads.

But once in space, objects remain there; they do not fall out of the sky like aircraft. There is no friction in space outside the Earth's atmosphere. Movement within the medium does not require constant propulsion. Once a satellite is orbiting, it will continue to orbit, even if every system aboard fails. The exceptions to this rule are the satellites which are in Low Earth Orbit (LEO). They will be dragged down by the
Earth's atmosphere.\textsuperscript{1} Because of the enormous costs involved in launching payload mass, satellites are quite fragile. And because of the high velocities required to orbit Earth, very small anti-satellite weapons can destroy very large satellites without ever accelerating to orbital velocity (see Chapter 5).

We have seen that as one moves from land to sea to air to space, military control of the medium represents a more abstract advantage. This is because the contents transmitted via that medium are more abstract. In the case of space, all that is important is obtaining information from the enemy and denying information to the enemy.

4.1.2 Earth Geography

Geography in space is a very different concept than geography on Earth. On Earth, the height of land and the depth of water are all relevant factors. One must walk or build railroads around mountains, or fly over them. Points of land must be rounded by sailing ships.

But in space there is no land, air, or water. The geography of space is a much more abstract concept. Space is a very uniform continuous environment, with no sudden changes. The three dominant features of space around Earth, in order of importance, are: the Earth's gravitational field, the Earth's rotation, and the Earth's atmosphere.

The Earth's Gravity is the Dominant Force

The Earth's gravitational field defines the laws of motion in space. To enter space one must fight this field, using much more energy than is required to get into the air. To stay in space also requires enormous energy expenditure to establish an orbit. Once in an orbit, however, this gravity constantly warps the velocity of the satellite, allowing it to effortlessly travel in ellipses, essentially forever.

In other words satellites must be moving very fast in order to go in circles. The speed required can be as much as eight kilometers per second in Low Earth Orbit

\textsuperscript{1}Satellites in LEO can depend on rockets to counteract atmospheric drag. If these rockets fail the orbit decays more quickly than if the system were still operating.
(LEO, 200km to 1500km altitude). Whereas an aircraft must expend fuel continuously while in the air,\(^2\) satellites expend almost no fuel to stay in space.\(^3\)

The further away a satellite is from the center of the Earth, the less orbital velocity is required to sustain the orbit. This would imply that higher orbits are easier to attain. But the cost of reaching those heights more than outweighs the slower orbital velocity required to stay there. Paradoxically, the fastest orbits (just above the Earth's atmosphere) are the easiest to attain.

**The Earth's Rotation is a Prevailing Wind**

The second geographic feature of Earth orbit is the fact that the Earth rotates. This fact identifies certain orbits that are particularly useful. In effect, the infinite set of all possible orbits is reduced to a much smaller set of useful ones. A spinning Earth with a gravity field creates a space geography.

A rotating Earth both defines and makes possible the geo-synchronous orbit (GEO). It defines a single orbit where the satellite remains motionless with respect to the surface of the Earth: one with a roughly 24 hour period at 35,785 km directly over the equator.\(^4\) This orbit is used for communications satellites. The satellites can be seen from a large area on Earth, and satellite dishes need not be constantly moved to track the satellites because the satellites do not move from any viewpoint of Earth. If the Earth did not rotate, this would not be possible. All satellites would move relative to the surface of the Earth.

A rotating Earth favors the launch of satellites in equatorial regions. The rotation of the Earth can impart from zero to 0.46 km/sec to the initial velocity of a rocket,

---

\(^2\)If an aircraft stops expending fuel, it becomes a glider and starts falling. Only with special wind conditions does a glider ever go anywhere but down to the ground below it.

\(^3\)Note that very low orbits require thrust to counteract atmospheric drag effects. Also, satellites usually require small amounts of thrust to maintain a precise orbit against gravitational perturbations. These perturbations come from the oblateness of the Earth (it's not quite round, it bulges around the equator, see Section 4.2.3 on p. 131) and from the gravitational fields of the Sun and Moon.

\(^4\)In fact while the Earth rotates once per day with respect to the Sun, the Earth rotates slightly slower than once per day with respect to the stars. In 24 hours, the Earth rotates once, plus a bit to compensate for its motion about the sun. This means that the GEO orbital period is actually 1436 minutes, rather than 1440 minutes (24 hours).
depending on latitude. This may seem a small fraction of the 8 km/sec needed to reach low Earth orbit (LEO), but because of the exponential nature of rocket propulsion, every little bit helps a great deal (more on rockets in Chapter 6). This also means that the vast majority of satellites are launched from West to East and orbit in that direction. Thus the rotation of the Earth functions as a kind of prevailing wind, which blows the satellite population from west to east (spinward). Anyone wishing to orbit in the other directions (requiring anti-spinward thrust) must pay a price for doing so. This effect decreases at higher latitudes (North or South) because the rotational velocity of the Earth decreases as one approaches either pole. Most launch pads are located near the Equator in order to maximize the spinward effect.

The Earth’s Atmosphere is a Shoal

The Earth itself is an obvious hazard in space. An orbit that intersects the surface of the Earth (6378km from the center) will not last long, nor will it experience a soft landing. This hazard is extended an additional 200 km outward by the Earth’s atmosphere. The Earth’s atmosphere creates friction which lowers orbital velocity. Lower orbital velocity results in a lower orbit, which increases friction as the atmospheric density increases. As Table 6.1 (p. 174) shows, below an altitude of 200 km, an orbit will not last long.

Thus, the Earth’s atmosphere acts as a navigational hazard, much as shoals are hazardous to ships. Satellites wishing to remain in orbit should stay clear of the atmosphere. Of course, since the cheapest orbits (and the best for viewing details on Earth like missile silos) are those close to the Earth’s atmosphere, some satellites want to go only as high as necessary.

But atmospheric density is an unpredictable thing, it varies with Sun spot activity. Table 6.1 (p. 174) shows only the range. Exact prediction is impossible. Satellites that live close to the Earth usually bring with them rockets to counter-act the effects of atmospheric drag. The fuel on board these rockets determines the satellite’s potential life expectancy. The variation in the atmosphere determines its actual lifespan.

Atmospheric drag can be used to assist a satellite in returning to Earth without
using large rockets, as Apollo and the Space Shuttle have done. When the Shuttle wishes to return, it uses a small rocket to lower its orbit enough to encounter the atmosphere. The heat shielding required to survive the encounter weighs much less than the fuel that would be required to slow the Shuttle further with its rockets.

**Rockets are the Means of Propulsion**

Rockets are the primary means of transport in space today. They provide change in velocity (acceleration or ΔV). Since everything in space moves, getting around in space is a matter of changing velocity. Rockets don’t “move” things in space, they change where their payloads are going. Thus, mission rocket requirements are expressed in terms of ΔV.

Rockets provide ΔV by igniting fuel which moves backward, which results in the rocket accelerating forward. It would be most efficient if all the fuel could be burned instantly, in one big explosion, but this presents certain engineering difficulties (like crew survival). Thus the fuel must be burned gradually. The trouble is, in order to keep burning fuel, the unburned fuel and the rocket motor must be accelerated along with the payload. This leads to exponential growth in terms of fuel cost, and therefore rocket size. In other words, it take more fuel to go from 2 km/sec to 3 km/sec than it does to go from 1 km/sec to 2 km/sec.

This is why small changes in required ΔV can lead to big changes in terms of rocket size. I construct a model of rocket performance and cost in Chapter 6.

**Summary of Earth Geography**

Space is a very hostile and expensive place. The only thing light enough to be economically transported in space is information. Putting craft into space is technologically difficult and expensive. Once orbit is achieved (above the Earth's atmosphere), changing direction is also expensive. The nature of rocket propulsion makes each additional maneuver more expensive than the last. In fact, all maneuvers must be anticipated before launch as the fuel for each of them must be launched along with the spacecraft.

The rotation of the Earth encourages most satellites to move from West to East.
There is no cover in space. Everything is visible. This fact, combined with the difficulties of changing directions means that a satellite’s position is space is highly predictable. Orbits are perturbed by the effects of Earth, Moon and Sun, but in predictable ways. The one unpredictable factor is low orbit lifetime, as the Earth’s atmospheric density varies considerably.

4.2 Earth Orbit

To understand the physics of movement in space near Earth, one must understand the physics of movement in the Earth’s gravitational field. In this section I characterize the Earth orbits that are important to the study of satellite attack and defense strategies.

4.2.1 Kinetic and Potential Energy

All orbits have a particular total energy that remains constant. This energy is the sum of kinetic energy (based on velocity) and potential energy (based on altitude) of an object in that orbit at any given point.

**Kinetic energy** is $\frac{1}{2}mv^2$, where $m$ (kg) is the mass of the moving object and $v$ (km/s) is its velocity. The higher the velocity, the higher the kinetic energy.

**Potential energy** is $-m\mu/r$, where $\mu$ ($km^3/s^2$) is a gravitational constant ($3.98601 \times 10^5$ for Earth), $m$ (kg) is the object mass, and $r$ (km) is the distance from the object to the center of the Earth. Potential energy is expressed as a negative quantity which climbs to zero as the object moves to an infinite distance from the Earth. In this thesis, I will call the distance from the center of the Earth *radius*, and the distance above the surface of the Earth *height or altitude*.

All orbital paths are conic sections (circles, ellipses, parabolas or hyperbolas). If the sum of its kinetic and potential energies is a negative number, then the orbit is elliptical or circular. If the object has zero total energy, it has just enough energy to escape from the Earth’s gravitational field and come to a halt an infinite distance from the Earth. These “escape orbits” take the shape of a parabola. If an object has
a positive total energy (i.e. it can escape from the Earth and still have a non-zero velocity), the shape of the orbit is a hyperbola.

All orbit shapes are conic sections. Conic sections are differentiated by eccentricity ($\epsilon$). Circles have an eccentricity of zero; for ellipses, $0 < \epsilon < 1$; for parabolas, $\epsilon = 1$; and for hyperbolas $\epsilon > 1$.

I am interested in orbits with energy less than zero, because they remain within the Earth’s gravitational field. These orbits are ellipses or circles ($0 \leq \epsilon < 1$). Circular orbits have a constant radius and velocity. Consequently their kinetic and potential energies remain constant. With ellipses, however, although the total energy remains constant, the energy is constantly being passed back and forth between kinetic and potential. When the object reaches perigee (the lowest point of the ellipse), the velocity is at its highest. When the object reaches apogee (the highest point of the ellipse) the velocity is at its lowest. The average of apogee and perigee is called “a” and is an important orbital parameter.

Figure 4-1 bounds the range of orbits of interest. The vertical axis represents the distance from the center of the Earth (the radius), the horizontal axis represents velocity (in any direction). Most satellites are at or below geosynchronous orbit (GEO), so the upper bound lies at that radius (42,370 km) and is represented by the solid vertical line near the top of the graph. The surface of the Earth is the lower bound of the graph, represented by the solid line at 6370 km, the average radius of the Earth.

The remaining curves (with one exception) are curves of constant total energy. They represent the trade-off between radius and velocity at various total energies. Total energy increases upward and to the right.

Along the solid curve at the highest energy level lie all escape orbits (i.e. all parabolic orbits which just go to infinity). This solid curve represents an upper bound on orbit energies I wish to consider. The lowest energy orbit possible is one that just skims the surface of the earth (ignoring atmospheric drag) in a circle. The lowest energy curve (also solid) represents all orbits of this energy: the lower bound.

The space enclosed between these four solid lines represents the energy levels of
Figure 4-1: Kinetic and Potential Energies of Earth Orbits
all orbits of interest to us. The **dashed** curves are curves of constant total energy in between these extremes. The highest dashed curve is the GEO orbit. The second highest dashed curve is the energy required to reach, but not to maintain, GEO radius—notice that the curve touches GEO radius as velocity comes to zero.

The **dotted** curve is **not** one of constant total energy. This line represents all the radius-velocity combinations that can produce circular orbits. For example, the lowest curve of constant energy, which represents a circular orbit along the Earth’s surface, intersects the dotted line just as it intersects the surface of the earth. This allows me to state that orbits of increasing altitude (increasing a) require less orbital velocity to sustain them.

**Principle of orbital velocity vs radius:** *As orbital radius (a) increases, total orbital energy increases and orbital velocity decreases.*

Those of us on the Earth’s surface spend most of our time in the lower left hand corner of the graph (depending on our latitude, our velocity ranges from 0 to 0.46 km/sec),[^5] where the Earth’s surface boundary intercepts the vertical axis. All ground-based rockets start with this total energy. Rockets receive some kinetic energy before launch due to the Earth’s rotation. This is why launching from northern latitudes is harder than launching from near the Equator. But most of a rocket’s initial total energy is potential energy derived from being 6370 km from the center of the Earth’s gravitational field.

### 4.2.2 Orbital Equations

This subsection is a bit of a digression. I was attempting to put together a simple, universal way of analyzing transfers from one ellipse to another, but I failed. Because it is possible to derive conclusions without a detailed analysis, I have stopped work along these lines. What remains are some rules I have assembled regarding ellipses which are of use later in this chapter.

The point at which the dotted line in Figure 4-1 intersects the curves of constant

[^5]: Velocity at the Equator is 0.46 km/sec. At latitudes north of the equator, the velocity of the surface of the Earth is: \( \cos(\text{latitude}) \times 0.46 \).
total energy has some interesting properties. But to explain them, I first need to talk more about ellipses. The key parameters of an ellipse are $a$, $b$, and $c$. The parameter $a$ is the semimajor axis, the distance from the center of the ellipse (half way between the two foci of the ellipse) to either perigee or apogee, or half the length of the ellipse. The parameter $b$ is the semiminor axis, the distance from the center of the ellipse to either side, or half the width of the ellipse. The parameter $c$ is the distance from the center of the ellipse to either focus. The center of the Earth lies at one of the foci. Here are some useful equations and statements about ellipses:

\[ a^2 = b^2 + c^2 \]

\[ \epsilon = \frac{c}{a} \]

- All orbits of the same total energy have the same size semimajor axis ($a$), and therefore the same period (see Equation 4.2).

- As eccentricity ($\epsilon$) goes from zero upwards, the distance of the center of the ellipse from the center of the Earth ($c$) goes from zero upwards ($\epsilon = c/a$).

Now consider the points where the dotted line intersects the curves of constant energy. For a given energy, if the eccentricity is zero the radius and velocity (perpendicular to the force of gravity) remain fixed, resulting in a circular orbit. If the eccentricity is increased (by altering the direction of the velocity), the ellipse’s radius/altitude point moves up and down the curve, oscillating between extremes of velocity/radius trade-offs, exchanging kinetic for potential energy and back again. The apogee and perigee of this ellipse are exactly $c$ above and below the point for a circular orbit (the point intersection with the dotted line), respectively.

Here are some useful elliptical equations:\(^6\)

\[ \frac{v^2}{2} - \frac{\mu}{r} = \text{Total Energy} = \frac{-\mu}{2a} \]  \hspace{1cm} (4.1)

---

Orbital Period (in sec) = $2\pi \frac{a^{3/2}}{\mu^{1/2}}$ \hspace{1cm} (4.2)

or

\[ a \text{ (in km)} = \left( \frac{\text{Period} \times \mu^{1/2}}{2\pi} \right)^{2/3} \] \hspace{1cm} (4.3)

The velocity at any given point in an elliptical orbit is:

\[ \text{Elliptical Orbital Velocity (in km/sec)} = \sqrt{\frac{2\mu}{r} - \frac{\mu}{a}} \] \hspace{1cm} (4.4)

The velocity at any given point in a circular orbit ($a = r$) is:

\[ \text{Circular Orbital Velocity (in km/sec)} = \sqrt{\frac{\mu}{r}} \] \hspace{1cm} (4.5)

where $a$ is in km, $\mu$ is $3.98601 \times 10^5 \text{ km}^3/\text{s}^2$, and $r$ is the radius of the satellite (distance from the center of the Earth) in km.

### 4.2.3 Perturbations in Low Earth Orbit

Satellites orbiting the Earth theoretically follow perfect elliptical orbits with a fixed orientation to the stars. That is, the satellite orbits the sun along with the Earth, but the plane of the satellite’s orbit remain inertially fixed, it does not rotate. This would be true if the Earth rotating beneath the satellites were a perfect sphere. In fact, the Earth is not a perfect sphere, it bulges near the equator. This oblateness causes the Earth’s gravitational field to be imperfect, which in turn, perturbs the orbits of satellites in LEO.\(^7\) Gravitational irregularities produce two effects on satellite orbits: east-west perturbations and north-south perturbations.

#### East-West LEO Perturbations

The first effect is that the plane of the orbit rotates about the the Earth’s axis. This shifts the ground track of the satellite eastward or westward (provided it has a

The orbital parameter which is altered is the right ascension, which is usually represented by the symbol $\Omega$. $\Omega$ is derived by finding the longitude at which the satellite ground track crosses the equator on its northward pass. The angle between this longitude and the longitude of the Vernal equinox is the right ascension $\Omega$. The Vernal equinox (represented by the symbol $\Upsilon$) is a reference point in the fixed star background. On other words $\Omega$ represents the angle between the plane of the orbit and the line from the Vernal equinox to the center of the Earth. One can think of it as an orbital longitude with respect to the stars. Increasing $\Omega$ moves the satellite ground track from West to East.

In a perfect gravity well, $\Omega$ would never change, but because of the Earth’s imperfections, it moves at the following rate:

$$\Delta \Omega = -\frac{3nJ_2R_e^2}{2a^2(1-e^2)^2} \cos i$$

where $\Delta \Omega$ is expressed in radians per second; $n$ is the mean motion equal to $\sqrt{\mu/a^3}$; $J_2$ is a dimensionless constant equal to 0.001082 which expresses the asphericity (oblateness) of the Earth; $R_e$ is the radius of the Earth, 6,378 km; $a$ is the elliptical parameter, the semimajor axis (the average of the apogee and perigee altitudes); $e$ is the eccentricity of the ellipse; $\mu$ is the gravitational parameter equal to $3.98601 \times 10^5 km^3/s^2$ (the mass of the Earth times the universal gravitational constant); and $i$ is the inclination of the orbit in degrees.

If we assume a circular orbit ($e$ equal to zero), collect terms, multiply out the constants, and change units, we get the following:

$$\Delta \Omega = -\frac{2.0635 \times 10^{14} \cos i}{\sqrt{a}}$$

---

8This reference point can be found by drawing a line from the Earth’s location on the first day of Spring, through the Sun, and through the Earth’s position on the first day of Fall. Another definition is the line which represents the intersection between the plane of the Earth’s orbit and the plane of the Earth’s rotation on the first day of Spring or Fall. Source: Space Handbook, p. 2-28.
where $\Delta \Omega$ is expressed in degrees per day. With this simplified formula we can make some observations. First, at inclinations of 90 degrees this effect is nil. Above 90 degrees the satellite track will drift eastward, below 90 degrees it will drift westward. Second, increasing orbital radius $(a)$ quickly reduces this perturbation to a negligible value. Its effects will be felt most in LEO at low inclination. At an altitude of 200 km $(a$ of 6578 km) and an inclination of 33 degrees, the drift per day would be 8.3 degrees. In GEO, this effect is negligible (see the next section for a discussion of GEO orbit perturbations).

There is another factor which moves the ground track of a satellite East or West regardless of altitude: the Earth’s rotation. During every satellite orbit, the Earth moves under the satellite. For a 90 minute period, this amounts to roughly 15 degrees latitude movement west on each pass. Now if the satellite’s period is an exact multiple of the rotational period of the Earth, those ground tracks will remain fixed; otherwise they will drift. The actual orbital period of the Earth (with respect to the stars) is 23.93 hours. A satellite must be synchronized with this period in order not to drift.

The Earth rotates once every 24 hours with respect to the Sun. But because the Earth orbits the Sun, the Earth actually rotates 360.98 degrees in 24 hours. If a satellite orbit is exactly 90 minutes, it will make exactly 16 orbits in 24 hours, but the Earth will have rotated 0.98 degrees eastward under it. Thus, if the satellite period is matched to 24 hours, the satellite will move west at 0.98 degrees per day.

By altering the period of the satellite slightly, the satellite can be made to drift East or West, adding or subtracting from the oblateness effects. Soviet reconnaissance satellites have done this to move their ground tracks during international crises.⁹

**North-South LEO Perturbations**

The second oblateness effect on LEO orbit is to rotate the orbit within the orbital plane. If the orbit is circular, this has no effect, but if the orbit is elliptical the effect is to shift the points of apogee and perigee.

The orbital parameter which is altered is the argument of perigee (\(\omega\)). This is the angle between the point at which the satellite crosses the equator moving northward (the ascending node) and the point at which the satellite reaches perigee. Thus if \(\omega\) is 90 degrees, perigee occurs at the northernmost point in the orbit; if \(\omega\) is 180 degrees it occurs at the equator on the southward pass; and if \(\omega\) is 270 degrees it occurs at the southernmost point in the orbit.

The equation for the daily change in \(\omega\) is almost identical to the change in \(\Omega\), but instead of \(\cos i\) we use \(\frac{5}{2} \sin^2 i - 2\). Thus, using the same units conversion as above, we get the equation\(^{10}\)

\[
\Delta \omega = \frac{2.0635 \times 10^{14}(\frac{5}{2} \sin^2 i - 2)}{\sqrt{a^7}}
\]

This effect is zero when \(\frac{5}{2} \sin^2 i - 2\) is zero. This occurs at inclinations of 63.43 degrees and 116.56 degrees. 63.43 degrees is the inclination used by Soviet Molnyia communications satellites. Much of the Soviet Union is too far north to see GEO communications satellites. Instead the Russians use satellites in highly elliptical orbits with their perigee at \(\omega = 270\) degrees.\(^{11}\) This means their apogee is at 90 degrees. In other words, they move slowly over the northern hemisphere and quickly over the southern one. The orbits have a period of 12 hours and are deployed in groups of four with ascending nodes 90 degrees apart.\(^{12}\) Thus while two satellites are at their perigees in the southern hemisphere, two satellites are at their apogees in the north: one over the U.S., the other over the U.S.S.R. If their inclinations were other than 63.43, their apogees would move gradually southward, reducing the time they spent over Russia and eventually they would become useless until their apogees rotated all the way back to the north.

\(^{10}\)Wiesel, p. 87.
\(^{11}\)Wiesel, p. 88.
\(^{12}\)Flight International, Volume 107, June 16th, 1975, p. 79.
4.2.4 Geosynchronous Orbital Perturbations

Perhaps I should take a moment to specify the GEO orbit. GEO orbit is directly above the equator, 35,787 km above the Earth’s surface. The orbital period is 1,436.2 minutes, 3.8 minutes less than 24 hours because the Earth over rotates 0.98 degrees in 24 hours. GEO orbital velocity is 3.074 km/sec. The orbit is basically permanent; satellites in GEO lose 1 km of altitude every 1000 years.

The reader can see that the LEO perturbation equations depend on a low semi-major axis (a) value for the orbit. As the a of the orbit increases, these perturbations quickly become negligible. At GEO, their effects are negligible and other forces come into play to perturb the orbit of satellites.\(^\text{13}\) As with the LEO perturbations, they can be divided into two groups: east-west and north-south.

East-West GEO Perturbations

The Earth’s equator is not an exact circle, the high point being 70 meters higher than the low point. This produces two points of very slight gravitational attraction at 107 degrees West (South of Denver) and 76 degrees East (South of Bombay).

Satellites in GEO will tend to drift toward the nearest of these points, then overshoot, slow, and drift back, much like a pendulum on a clock. This pendulum, however, moves very slowly; the period of each complete oscillation is 820 days (2.25 years). Of course, satellites stationed at 107 West or 76 East do not move, just as a pendulum released at its lowest point does not move. Because the damping forces in space are minimal, this oscillation will continue forever unless something interrupts it.

This force is very slight and is easily overcome. At most, a \(\Delta V\) of 2.1 m/sec (0.002 km/sec) per year is required. Thus, maintaining a satellite’s east-west position is easy, consuming at most 0.1% of the satellite’s mass per year.

North-South GEO Perturbations

The inclination of GEO satellites is altered by the gravitational forces of the Sun and Moon. Starting from zero, the satellite’s inclination will change at 0.86 degrees per year. This change will gradually lessen and then stop at 15 degrees, 27 years later. The satellite will then move back toward a zero degree inclination over the next 27 years. Then the process will repeat.

Again, this force is very low. Satellites can maintain a zero degree inclination with a $\Delta V$ of 55 m/sec (0.055 km/sec) per year. This will consume, at most, 2.3% of the satellite’s mass per year.

This concludes the orbital reference section. Much of what has been listed here is used elsewhere in the dissertation. Armed with all this information, we now proceed to examine the implications of different ASAT trajectories in the next section.

4.3 Methods of Attack

We now turn to the practicalities of destroying satellites in orbit by conventional means. The question addressed in this section is one of deliverability: Can we effectively deliver the means of destruction to the target? In the next chapter, I determine how easily a properly placed ASAT can destroy a target satellite (see Chapter 5, p. 154).

A World War II example of a deliverable munition is the torpedo. A small, frail torpedo bomber can sink a large, well armored battleship. The un-armored aircraft can prevail over the battleship because it can effectively deliver its means of destruction beyond the effective range of the battleship’s guns.

Of course, even when it is possible to effectively deliver the means of destruction to the target, the effects of detection, concealment and decoys all come into play to determine the outcome. I will examine these factors in later chapters, but first I must establish whether or not satellites can be easily destroyed in a war of maneuver. In this chapter, I will give the attacker the benefit of the doubt regarding satellite detection, decoys, etc.
I will focus on impact kills. Destruction at a distance (lasers and electronic means of neutralization) will also be considered in later chapters. Physical attack of a satellite can be divided into two types: co-orbital and pop-up. We will evaluate the cost of each type of attack. The measure of “cost” in this section will be $\Delta V$. Later, in Chapter 6, we will see how $\Delta V$ translates into rocket mass.

In a co-orbital attack, the ASAT moves into an orbit close to that of its target. It then maneuvers to intercept, using slight differences in orbital characteristics to bring them together. This is like bumping into an adjacent car on the freeway. Although both cars are speeding along, the impact velocity is quite low.

A pop-up attacker simply launches straight upwards, reaching the target satellite’s orbital altitude just as it passes overhead. This is like dropping a rock from an overpass onto a car on a freeway. Timing is crucial. Although the rock is moving slowly, the car’s speed creates a violent impact.

4.3.1 Co-Orbital Assault

A co-orbital attack is one in which the attacker moves into an orbit that closely matches that of the target in position, velocity, and time. The closing velocities are low by orbital standards. The attacker then destroys the target as the two come together. In the case of the Soviet ASAT (the only tested co-orbital ASAT system), an explosive is fired just prior to intercept to spread out a swath of pellets. The closing velocity of the pellets is low, but when combined with the velocity imparted by the explosive, it is sufficiently high to damage the target.

The co-orbital assault is used when the interception mechanism is incapable of dealing with high closing velocities. But we also want to know if a co-orbital system with a high closing velocity interceptor has any advantages over its target. A low closing velocity attack profile is no longer required if the attacker has a high speed interceptor.

Presumably, with warheads capable of intercept at high closing velocities, co-orbital systems could use them as destruct mechanisms, invalidating the need for heavy packages of pellets and explosives. The one advantage the pellets have over the
new systems is a higher kill radius. The Soviet ASAT has a kill radius on the order of one km,\textsuperscript{14} while the direct impact systems’ kill radii vary from 30 cm to 4.6 m.\textsuperscript{15}

Another advantage co-orbital systems have over pop-up ASAT’s is that they have more time to inspect their target as they approach, due to a lengthy approach and a lower closing velocity. Of course the target also has more time to deploy decoys and this may have implications for dealing with decoys—but I will take this up in a later chapter.

The questions we wish to answer are: Does co-orbital attack provide any physical advantages for either side in the maneuver/counter-manuever game? If a high-speed intercept is possible, are their advantageous attack profiles available? In order to evaluate this form of attack, make the following assumptions:

- Perfect information is available: complete information, instantly transferred on both sides
- The target satellite is initially in a circular orbit
- Attacker uses Hohmann transfer orbit (see below) to the intercept target
- The target has maneuver capability
- No decoys or self-defense kill mechanisms are present
- Maneuvers are executed in single impulses (i.e. zero burn times).
- Earth rotational velocity imparted to the attack on launch is ignored
- Earth atmosphere is ignored

\textsuperscript{14}Up until 1981, the U.S.A.F. claimed the kill radius of the Soviet ASAT was 1 km; since then the claimed kill radius has grown to 8 km (5 miles). (See \textit{An Illustrated Guide to Space Warfare} by David Hobbs, Salamander Books, Ltd., 1986. An Acro Military Book, published by Prentice Hall Press, New York, p. 93). I have good reason to doubt the 1 km claim, let alone the 8 km one. See Appendix A for a more detailed discussion.

\textsuperscript{15}The three I know of are all U.S. systems. These are: the U.S.A.F.’s MHV fired from an F-15 with a kill diameter of 30.5cm (12 inches); the U.S. Army’s Homing Overlay Experiment (HOE), kill diameter is 4.6m (15 ft.); and the SDIO’s latest “brilliant pebbles” scheme, with a kill diameter of 1m. Sources: \textit{An Illustrated Guide to Space Warfare} by David Hobbs, Salamander Books, Ltd., 1986. An Acro Military Book, published by Prentice Hall Press, New York, p. 123 & p.88. Also, \textit{Aviation Week & Space Technology}, 2/26/90, p.62.
• Launch site is co-planar with target orbit (later relaxed)

Ascent Time and Cost

The minimum energy orbit required to go from one orbit to another is called the “Hohmann transfer.” Basically, it’s an ellipse which is tangential to both orbits. For a co-orbital attack, the initial ASAT orbit is an ellipse that is tangential to the surface of the Earth and the circular target orbit.

The ASAT is not in orbit to begin with, but Equation 4.4 on page 131 can be adapted. The necessary $\Delta V$, starting from the surface of the Earth, is given by:

$$\Delta V = \sqrt{\frac{2\mu}{R_e} - \frac{\mu}{(R_e + R_t)/2}}$$

where $R_e$ is the Earth’s radius and $R_t$ is the radius of the target.

For a target with an altitude of 200 km, the $\Delta V$ is 7.9662 km/sec—a $\Delta V$ very close to that required to achieve orbit at that altitude. At 200km the target is moving at 7.843 km/sec (from Equation 4.5). We can determine the velocity of the attacker using Equation 4.6 and substituting $R_t$ for $R_e$ in the denominator of the first term. This gives us a apogee velocity of 7.724 km/sec. The difference in $\Delta V$ is 0.0603 km/sec. Thus, in terms of $\Delta V$ required, co-orbital assaults provide almost no attacker advantage.

The time required to perform this maneuver is one half of the ellipse’s period (the transfer is a half orbit). The period of an ellipse can be computed with Equation 4.2. The $a$ of the transfer orbit is the average of its perigee ($R_e = 6378$ km) and apogee ($R_t = 6578$ km). The period is 5189 seconds or 86 minutes. The ascent time is half the period of the ellipse or 43 minutes.

---

Evasion by Plane Change

I now turn to the question of target maneuvers to avoid intercept. The first of these to be considered is changing the plane of the orbit to avoid the intercept point. In order to maximize the distance from the intercept point, the plane change should occur 90 degrees\(^{17}\) prior to the intercept point.

As a counter, the attacker could alter its plane to try to move the initial intercept point to touch the new altered attacker orbit. But since the attacker is lower, its velocity is greater, so a plane change is costlier. Also the attacker (having a higher velocity than the target for most of the ascent) will almost certainly be beyond the optimal point for a plane change (90 degrees from perigee, measured from the Earth’s center the *semilatus rectum*). The plane change required will therefore be greater in angle than that made by the target. In addition, an attacker plane change after this point will not be sufficient to intercept. An increase in size of the ellipse will also be required to intersect with the new target orbit.

But the attacker has a better counter maneuver available: once the interceptor reaches apogee, it can burn to achieve a circular orbit that will intersect with the new target orbit. Total \(\Delta V\) for the target is greater than \(\Delta V\) for the interceptor by the amount needed for the plane change. Intercept is delayed by some fraction of an orbit which is less than half (probably 1/4 orbit, given the optimal point to make the defensive plane change is 1/4 orbit away from the initial intercept point).

Thus, the plane change turns out to be a poor defensive maneuver. The attacker has a good countermove: continue to the initial intercept point, burn to circularize the orbit, and intercept one quarter orbit later than originally planned. Plane changes, at best, delay intercept by less than 1/2 orbit, and still cost more \(\Delta V\) for the target than the attacker.

\(^{17}\)That is when the angular distance between the satellite and the point of intercept reaches 90 degrees. One can also think of it as the point where the vector from the center of the Earth to the satellite and the vector from the center of the Earth to the satellite’s orbital perigee are at right angles to each other. For both circular and elliptical orbits, the position vector at this point is called the *semilatus rectum* or \(p\) which is equal to \(a(1 - e^2)\).
Evasion by Elliptical Orbit

A better evasion technique is to boost the target into an elliptical orbit. This too avoids the initial intercept point. If the attacker uses the same counter maneuver as described above and boosts to circular orbit at the initial intercept point, again there is a point of intersection of the two orbits (some 3/4 orbit later). However, because the higher orbit is slower, the two orbits are out of phase. The two orbits are tangent, but the attacker and the defender arrive at that tangent point at different times. It may be many orbits before intercept can occur.

As an alternative counter measure, the attacker could boost to the same sized elliptical orbit when it reaches the initial intercept point. The two identical ellipses would be offset about 90 degrees from each other. There would be two points of intersection and the periods of the two orbits would be the same. But because the two orbits were entered at different times, they are out of phase and the satellites will never meet.

Alternatively, the attacker could boost into the circular target orbit, then wait until he reaches the point where the target boosted into an elliptical orbit and follow it by boosting into exactly the same orbit. The attacker is now in the same orbit as the target, but again, because it entered it at a different time, the satellites will never meet.

How costly would it be for the attacker to catch up to the target? First we must determine the time difference between them. The time difference is equal to the difference in period between the target's initial circular orbit and the target's new elliptical orbit \((\Delta P_t = P_e - P_c)\). As the attacker moves in the circular orbit to the point where the target boosted into the elliptical orbit, the time will be one rotation in the circular orbit since the target boosted, i.e. the difference in periods \((\Delta P_t)\). That is, the target will return to the boost point after one period of the elliptical orbit, which is equal to one circular orbit period plus the difference between the circular and elliptical orbit periods \((P_e = P_c + \Delta P_t)\).

\(^{18}\)Note from the formula for the period of an ellipse, the greater the semimajor axis (the \(a\) value), the greater the period.
If the attacker now boosts into an elliptical orbit which has twice the period difference of the target's ellipse \((Pc + 2 \times \Delta Pt)\), then it will intercept the target one period later. Since the attacker has twice the delay (period difference) the period difference accumulated in one attacker orbit will be the sum of the delays (period differences) of two target orbits.

Now, how expensive (in terms of \(\Delta V\)) are increases in orbital periods? For small changes in orbits, the following equations apply:19

\[
\Delta V \approx V_{\text{orbit1}} - V_{\text{orbit2}} \quad (4.7)
\]

\[
\frac{2 \times \Delta V}{V_{\text{orbit}}} \approx \frac{\Delta \text{radius}}{\text{radius}} \quad (4.8)
\]

By looking at Equations 4.7 and 4.8, we can see that both the change in orbital velocity and the change in orbit radius are linearly related to \(\Delta V\). Since orbital period is time required to move through the orbital circumference at orbital velocity; and since the orbits here are roughly circular (small elliptical permutations of a circular orbit), then orbital velocity varies little and circumference is roughly \(2\pi r\).

For small changes, the orbital period is linear with respect to orbital velocity and radius. Since the above equations state these parameters are linearly related to \(\Delta V\), we can state that orbital period is linearly related to \(\Delta V\). Another way of putting it: looking at equation 4.2, we are saying that this curve is linear for small changes in \(a\).

Thus, to move into an ellipse with twice the increase in orbital period, the attacker must use roughly twice the \(\Delta V\). Intercept will occur roughly one and a half orbits later than originally intended.

Of course, the target can maneuver again before this intercept occurs. But the calculations for intercepting again are identical to those we have just computed. The target can delay the intercept for another one and a half orbits, and force the attacker to pay twice the \(\Delta V\) cost. But the target must keep maneuvering. As soon as it stops,

---

intercept occurs roughly \((1.5 \times 90\) minutes) 135 minutes later for a LEO intercept, or 1.5 days later for a GEO intercept.

Thus, by using elliptical orbit evasion, the target can avoid intercept while using half as much \(\Delta V\) as the attacker. This appears to be the target’s best defense. By using a higher radius, the target is able to get out of phase with the interceptor at a fairly low cost. Is there another course of action available to the attacker?

Perhaps a better method of attack is to come at the opponent from the other direction. When the attacker reaches the target’s initial orbit, he burns to stay there. When he reaches the point where the target thrusted to avoid intercept, he also thrusts to put himself in the identical orbit, but moving in the opposite direction. Intercept occurs only one half orbit later than intended (roughly), and \(\Delta V\) expended by the attacker is the same as that expended by the defender. There are two drawbacks to this type of attack. First, the attacker must have an interceptor capable of making high-speed intercepts. Second, the attacker must launch against the spin of the Earth. This can cost up to \(0.46 \times 2 = 0.92\) km/sec cost if both the attacker and defender launched from the equator. This additional cost may be partially compensated for by the fact that the impact velocity is higher, so a destruct mechanism is not required. This lowers the interceptor mass significantly.

**High Energy Transfers**

What if the attacker abandons the Hohmann transfer orbit as an attack trajectory? Instead of waiting to react to the defender’s defensive ellipse maneuver, the attacker could instantly thrust to re-establish intercept. How costly will that be? This is a hard question. The attacker must alter his ellipse to touch the target’s ellipse. But even more difficult, he must intersect the target orbit at the correct time. The attacker, in order to reach the target, may have to intercept earlier than the apogee of the target ellipse.

Incidentally, this means that the intercept will occur at a higher relative velocity since the angle of incidence between the two orbits is not zero (i.e. they are not tangential). This will require a high speed intercept warhead.
Figure 4.2: Attempt to Intercept in 90 Degrees
Note: the dotted line indicates a Hohmann transfer intercept over 180 degrees.

This will involve a non-tangential intercept with a higher $\Delta V$ cost, much higher than twice what the target expended. Getting places in orbit quickly always costs much more than getting places slowly. How much is much more?

Let us examine the case of an ASAT in LEO attempting to intercept a target in GEO at an orbital angle half that of the Hohmann transfer orbit. That is, intercept occurs after 90 degrees instead of 180 degrees (see Figure 4.2). The formulas for conic sections (circles, ellipses, parabolas, and hyperbolas), and eccentricity (zero for circles, between zero and one for ellipses, one for parabolas, and above one for hyperbolas) are:

$$R = \frac{a(1-e^2)}{1+ecos(v)} \quad (4.9)$$

$$e = 1 - \frac{R_p}{a} \quad (4.10)$$

where $a$ is an orbital parameter (average if perigee and apogee), $e$ is the eccentricity, $v$ is the angle of the satellite from perigee, and $R_p$ is the radius of perigee. Now, we want to assess the costs of adopting a transfer orbit (which must be a conic section)
from LEO to GEO. Our intercept should occur earlier than that with a Hohmann transfer orbit, where intercept occurs when \( v = 180 \) degrees.

Let ignore the issue of timing for the moment and calculate the costs of simply intersecting the GEO orbit at an angle of 90 degrees. I assume that we enter the transfer orbit by applying a tangential \( \Delta V \) in order to minimize losses and to limit the range of possible transfer orbits to a simple small set.

We know that the target orbital radius \( R \) to be 42,163 km (GEO radius) and that the perigee of our transfer orbit \( R_p \) will be 6578 km (LEO radius), and the \( v = 90 \) degrees (\( \cos(v) = 0 \)). We can recombine the above two equations and solve for \( a \) in terms of \( R \) and \( R_p \):

\[
a = \frac{-R_p^2}{R - 2R_p}
\]

Note that if \( R \) is less than twice \( R_p \) then \( a \) is positive and the transfer orbit is an ellipse. If \( R \) is exactly twice \( R_p \) then \( a \) is infinite and the transfer orbit is a parabola. If \( R \) is more than twice \( R_p \) then \( a \) is negative and the transfer orbit is a hyperbola. In this case, \( a \) is -1,492 km and the transfer orbit is a hyperbola. This means that the transfer orbit requires enough energy to escape the gravitational field of Earth and continue onward.

Now we can use the total energy equation 4.1 to determine the necessary \( \Delta V \).

A circular orbit in LEO has a total energy of -30.30 MJ/kg. A transfer orbit to GEO which intercepts a \( v = 90 \) degrees would have an \( a \) of -1,492 km, for a total energy of 133.6 MJ/kg. That is a change in total energy of 163.9 MJ/kg. To enter this transfer orbit the ASAT in LEO would have to accelerate from 7.78 km/sec to 19.71 km/sec, a \( \Delta V \) of 11.93 km/sec. A normal Hohmann transfer would require a total energy of 8.18 MJ/kg for a \( \Delta V \) of 2.46 km/sec. The hyperbolic transfer requires only 40 minutes to reach GEO, while a Hohmann transfer takes 315 minutes.\(^{20}\) For transfer to Semi-Synchronous Orbit (SSO, the orbit used by navigation satellites),

\(^{20}\)The hyperbolic transfer time is based on computer simulation. The Hohmann transfer time is calculated using Equation 4.2, with an \( a \) of \((32,163 + 6578)/2 = 24,370 \) km.

145
the numbers are 7.87 km/sec versus a Hohmann transfer orbit requirement of 2.08 km/sec. The times are 33 minutes versus 177 minutes.

Thus, transfer orbits which intercept at orbital angles half that of the Hohmann transfer orbit, to orbits with radii twice that of the initial ASAT radius, require parabolic transfer orbits (enough to escape the Earth’s gravity). Transfer orbits to orbits more than twice the initial radius, or to earlier intercept points are hyperbolic. In other words they are expensive, very expensive.

Now, coming back to the issue of timing, the conclusion is that any significant departure from the Hohmann transfer orbit in order to intercept an evading target will be more expensive than using a Hohmann transfer to catch the evading target.

This is explains why this chapter has focused on Hohmann transfer orbits for maneuver and counter-manuever. High energy transfer orbits are simply too expensive to consider.

In summary then: In the absence of defensive maneuver, executing a co-orbital attack costs the attacker almost as much $\Delta V$ as the target expended getting into orbit. If the target knows it is under attack and defensively maneuvers, it will be able to force the attacker to expend twice $\Delta V$ the target expends in final maneuver in order to intercept. If the attacker has a high-speed intercept capability, however, the attacker can attack head-on. While this has the disadvantage that the attacker must launch against the rotation of the Earth, the attacker can counter any defensive maneuver at equal cost to the defender.

Launch Site Considerations

What if the launch site is not in the plane of the target orbit at the time the attacker launches? The attacker can launch into a orbit which intercepts the target, but if he does not have a high speed intercept capability, then he must execute a plane change and the point of intercept to produce a low closing velocity. The cost of this plane change depends on the angle between the orbits at the point of intercept. At most it will be 90 degrees. To execute a 90 degree plane change requires $\sqrt{2} = 1.41$ times the orbital velocity. In other words, plane changes can be very expensive.
A plane change can be avoided if the attacker is willing to wait until the target orbit is over the attacker's launch site. This occurs once every 12 hours for most targets. The one exception is if the target orbit inclination is lower than the attacker's launch site. Most satellites in LEO and Semi-Synchronous Orbit (SSO) have a high inclination (60 degrees or more) in order to cover as much of the surface of the Earth as possible, with the exception of GEO satellites. If the attacker is willing to wait, then the attacker/defender advantage depends on the target orbit inclination and the latitude of the launch sites of the attacker and defender. The launch site with the latitude closest to the orbital inclination has a slight advantage.

The only exception are GEO satellites, which have a zero inclination. But since most launch sites are not on the equator, they satellite launcher must make a plane change to enter GEO orbit. Thus in the case of GEO targets, the relative advantage between attacker and defender is in the latitude of their respective launch sites. The one with the lower latitude has an advantage.

Thus, if an co-orbital attacker is willing to wait until the target orbit is overhead, he can avoid having to make any plane changes. Under these circumstance, the side with a launch site latitude closest to the target orbital inclination had an advantage.

**Summary of Co-Orbital Attack**

Co-orbital attack can provide a low closing velocity intercept if high speed interceptors are not available. Co-orbital intercepts require ΔV's only slightly less than the defender used to achieve orbit. Co-orbital intercepts also provide the defender with counter moves that force the attacker to use twice as much ΔV as the defender used during final maneuvers. Finally, if high speed interceptors are available, then the attacker cost can be held equal to the cost of the maneuvering defender (with an initial launch cost imposed by Earth rotation). This gives us the following principle:

**Principle of Co-Orbital Assaults:** Co-orbital attack trajectories provide no leverage for the attacker in terms of ΔV. If the target can maneuver and knows it is under attack, it can force the attacker to pay a twice the ΔV cost during final maneuvers to achieve intercept.
Next we move on to pop-up assault. A method of attack which gives the attacker a substantial advantage.

### 4.3.2 Pop-Up Assault

The previous section demonstrated that co-orbital assault does offer the attacker the advantage of a low closing velocity. But from a ΔV perspective, it does not give the attacker any leverage. I now examine the pop-up assault. I make the following assumptions:

- Perfect information: total information, instantly transferred
- Target satellite initially in circular orbit
- Target has maneuver capability
- No decoys or self defenses present
- Maneuvers are executed in single impulses (i.e. zero burn times)
- Earth rotation is ignored
- Target and interceptor must first come up vertically to 200km altitude before thrusting horizontally to avoid atmospheric effects
- Launch site is co-planar with target orbit (later relaxed)

The attacker launches straight upwards to achieve the same altitude as the target. This mode of attack has the great advantage that no velocity at the target altitude is required. The attacker times her launch to crest at the correct altitude just as the target passes by. Rather than establishing orbit, the attacker simply needs to reach the target’s orbital altitude for a moment—the moment when the target arrives.
Change in Total Energy Assessment

This approach provides a substantial advantage in terms of energy required for the attacker. The total energy (kinetic energy plus gravitational potential energy) per kilogram will be:

\[
\text{Total Energy (in MJ/Kg)} = \frac{v^2}{2} - \frac{\mu}{r}
\]

where \(v\) is orbital velocity in km/sec, and \(r\) is the distance from the center of the Earth in km.

We will use a simplified launch model which assumes that launchers first thrust upward to 200 km and then thrust horizontally to provide orbital velocity (for more details see Chapter 6). Thus, we will use 200 km altitude with no velocity as the base requirement for all attackers and defenders regardless of final altitude. That is, we assume that all satellite and ASAT launchers must first reach a 200 km altitude before any other maneuvers are performed.

The pop-up attacker only needs to reach the intercept radius \(R_{int}\). That is, acquire enough kinetic energy (in the form of velocity) to be converted into potential energy to reach \(R_{int}\). The necessary energy is the difference in potential energy per kilogram (\(\mu\)) at \(R_{int}\) minus the potential energy per kilogram 200 km above the surface of the Earth \(R_{200km}\):

\[
\Delta E_{\text{Energy}} = \frac{\mu}{R_{200km}} - \frac{\mu}{R_{int}}
\]  

(4.11)

This is the attacker’s energy requirement. Now consider the energy required by the target satellite to reach its circular orbit. The necessary velocity to maintain a circular orbit at a given radius \(r\) is \(\sqrt{\frac{\mu}{r}}\). Since \(r\) in this case is \(R_{int}\), \(v_{\text{orbit}} = \sqrt{\frac{\mu}{R_{int}}}\). Substituting \(v_{\text{orbit}}\) into the kinetic energy equation (again, for a unit mass) \(KE = \frac{v^2}{2}\), we get

\[
\Delta E_{\text{Energy}} = \frac{\mu}{2 \times R_{int}}
\]
In addition, the orbiting satellite must achieve the radius of the circular orbit (otherwise the orbit will be elliptical). This second energy requirement is the same as the attacking interceptor.

Thus, the total energy to get a target satellite of unit mass into a circular orbit of radius $R_{int}$ is:

$$\Delta E_{nergy} = \left(-\frac{\mu}{R_{200km}} - \frac{\mu}{R_{int}} + \frac{\mu}{2 \times R_{int}}\right)$$

This is the target’s energy requirement. Comparing the energy equations for attacker and target, we see that they differ in the amount $\frac{\mu}{2 \times R_{int}}$, a term which decreases with radius. Thus, the difference is more significant in LEO than in GEO.

But how does energy translate into $\Delta V$? One might be tempted to simply adapt the kinetic energy equation to translate change in energy into $\Delta V$:

$$\Delta V = \sqrt{2 \times \Delta E_{nergy}}$$  \hspace{1cm} (4.12)

By combining Equation 4.11 with Equation 4.12 we get:

$$\Delta V = \sqrt{2 \times \left(\frac{\mu}{R_{200km}} - \frac{\mu}{R_{int}}\right)}$$  \hspace{1cm} (4.13)

I can then derive the results in Table 4.1.

But we must use this equation with caution. This direct conversion of $\Delta E_{nergy}$ into $\Delta V$ only works if all the acceleration is performed at launch. Thus, the equation is sufficient to determine the $\Delta V$ needed to pop up to a particular altitude (ignoring Earth atmosphere and rotation). But this equation does not provide the actual $\Delta V$ required to achieve an orbit. This is because orbital maneuvers require at least two accelerations. The second acceleration occurs at a higher altitude than at launch. In order to accelerate above the initial launch altitude, an additional rocket must be lifted with the payload. This introduces losses (wasted energy) which is not accounted for by this equation. It is these losses which the Hohmann transfer orbit minimizes by maximizing the $\Delta V$ at the beginning of the maneuver and minimizing the $\Delta V$ at
<table>
<thead>
<tr>
<th>Mission</th>
<th>Orbit Reached</th>
<th>$\Delta V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pop-up from LEO (200 km) to 1500 km</td>
<td>ULEO</td>
<td>4.47 km/sec</td>
</tr>
<tr>
<td>Pop-up from LEO (200 km) to 20,183 km</td>
<td>SSO</td>
<td>9.55</td>
</tr>
<tr>
<td>Pop-up from LEO (200 km) to 35,785 km</td>
<td>GEO</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Table 4.1: Pop-up Mission $\Delta V$ Requirements

Note: ULEO stands for Upper Low Earth Orbit. SSO and GEO altitudes are based on 12.0 hour and 23.93 hour periods, respectively. The GEO period is slightly less than 24 hours because the Earth rotates slightly more than once per day relative to the stars. This slight over-rotation compensates for the motion of the Earth around the Sun, putting the Sun in the same point as viewed from Earth every day (which is how the 24 hour time interval was originally calculated). The GPS satellites in SSO do not seem to be based on this “sidereal day,” but instead actually have a 12.0 hour period (see Boden, Daryl “Introduction to Astrodynamics” in Wertz, James R. and Wiley J. Larson (editors), *Space Mission Analysis and Design*, Kluwer Academic Publishers, Dordrecht, Boston, and London, 1991, Figure 8-11, p. 140.).

<table>
<thead>
<tr>
<th>Mission</th>
<th>Equations Used</th>
<th>$r$</th>
<th>$a$</th>
<th>Initial Velocity</th>
<th>Burn-Out Velocity</th>
<th>$\Delta V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units:</td>
<td></td>
<td>km</td>
<td>km</td>
<td>km/sec</td>
<td>km/sec</td>
<td>km/sec</td>
</tr>
<tr>
<td>200 km to LEO</td>
<td>4.5</td>
<td>6578</td>
<td>-</td>
<td>0</td>
<td>7.78</td>
<td>7.78</td>
</tr>
<tr>
<td>LEO to ULTO</td>
<td>4.4 &amp; 4.5</td>
<td>6,578</td>
<td>7,228</td>
<td>7.78</td>
<td>8.13</td>
<td>0.342</td>
</tr>
<tr>
<td>ULTO to ULEO</td>
<td>4.4 &amp; 4.5</td>
<td>7,878</td>
<td>7,228</td>
<td>6.79</td>
<td>7.11</td>
<td>0.327</td>
</tr>
<tr>
<td>LEO to STO</td>
<td>4.4 &amp; 4.5</td>
<td>6578</td>
<td>16,569</td>
<td>7.78</td>
<td>9.86</td>
<td>2.08</td>
</tr>
<tr>
<td>STO to SSO</td>
<td>4.4 &amp; 4.5</td>
<td>26,560</td>
<td>16,569</td>
<td>2.46</td>
<td>3.89</td>
<td>1.43</td>
</tr>
<tr>
<td>LEO to GTO</td>
<td>4.4 &amp; 4.5</td>
<td>6578</td>
<td>24,370</td>
<td>7.78</td>
<td>10.24</td>
<td>2.46</td>
</tr>
<tr>
<td>GTO to GEO</td>
<td>4.4 &amp; 4.5</td>
<td>42,163</td>
<td>24,370</td>
<td>1.59</td>
<td>3.07</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Table 4.2: Orbital Mission $\Delta V$ Requirements

Note: ULEO stands for Upper Low Earth Orbit, ULTO stands for Upper LEO Transfer Orbit

the end of the maneuver.

Thus, in order to determine the $\Delta V$ for multiple acceleration missions, we will have to add up the $\Delta V$ required at each acceleration point. This will always total more in kinetic energy than the change in total energy of the satellite.

Fortunately, computing the orbital $\Delta V$ mission requirements is very simple. First we compute the $\Delta V$ required at each acceleration step in the mission, then we add up the totals and compare. The results are shown in Table 4.2.

We will assume that each mission starts at 200km with no orbital velocity. Since both attacker and target must pay the costs of reaching 200km, this will not affect
<table>
<thead>
<tr>
<th>Orbit Altitude</th>
<th>Attacker $\Delta V$</th>
<th>Target $\Delta V$</th>
<th>Attacker Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 km, LEO</td>
<td>0.00 km/sec</td>
<td>7.78 km/sec</td>
<td>7.78 km/sec</td>
</tr>
<tr>
<td>1500 km, ULEO</td>
<td>4.47</td>
<td>8.45</td>
<td>3.98</td>
</tr>
<tr>
<td>26,560 km, SSO</td>
<td>9.55</td>
<td>11.29</td>
<td>1.74</td>
</tr>
<tr>
<td>42,163 km, GEO</td>
<td>10.12</td>
<td>11.72</td>
<td>1.60</td>
</tr>
</tbody>
</table>

Table 4.3: Comparison of $\Delta V$ Requirements for Pop-Up Attacker vs Target Satellite
Note: ULEO stands for Upper Low Earth Orbit. Baseline for comparison is 200 km with zero velocity.

our comparisons. The $\Delta V$ required to reach 200km (including gravitational and rotational effects) is calculated in Section 6.3, p. 176.

First in the table is the requirement to go from a 200 km altitude to a circular orbit at 200 km (LEO). We can determine the velocity using Equation 4.5 and plugging in 200 km + 6378 km = 6578 km as a radius.

Next, we go from LEO to a Hohmann transfer orbit to semi-synchronous orbit (SSO). This is a semi-synchronous transfer orbit (STO). We begin by determining the radius of a SSO. Using equation 4.3 we can plug in a period of 12 hours (3600 x 12 = 43,200 sec) to determine the radius: 26,560 km. Now we use Equation 4.4 to determine the velocity. $a$ is the average of the two radii 26,560 km and 6578 km. $r$ is 6578 km. The result is 9.858 km/sec. Subtracting LEO orbital velocity, we get a $\Delta V$ of 2.07 km/sec.

Next we compute the acceleration from the apogee of the Hohmann transfer orbit (just as it touches SSO) to SSO. Using Equation 4.5, we know that the circular velocity in SSO (radius 26,560 km) is 3.89 km/sec. Using Equation 4.4, with the same $a$, but with an $r$ of 26,560 km, we get an apogee velocity of 2.46 km/sec. Subtracting the two we get a 1.43 km/sec requirement.

Table 4.2 also lists the calculations for Upper Low Earth Orbit (ULEO) at 1500 km altitude, GEO, and the necessary transfer orbits. Now we can compare the $\Delta V$ requirements for a pop-up attacker versus a target satellite. The comparisons are listed in Table 4.3. Note that the attacker advantage diminishes with altitude.

At a height of 200 km (6570 km radius), the target requires a $\Delta V$ of 7.78 km/sec to achieve orbit. The pop-up attacker would require no additional thrust to attack.
At a height of 1500 km (7878 km radius), the numbers are 8.45 km/sec and 4.47 km/sec, respectively. At GEO (height 35,785 km, 42,163 km radius), the numbers are 11.72 km/sec and 10.12 km/sec.

Impact of Launch Site Location

One drawback of pop-up attacks is that they don't go very far. Consequently, the launch site of the attacker must be in or very close to the orbital plane of the target satellite. If the attacker were to try to intercept a target in an orbital plane far away, this would constitute a co-orbital attack, with all of its consequent disadvantages.

At first glance, it might seem that this constraint is a serious drawback. Two factors mitigate its importance, however. First, with the advent of air-launched orbital systems (the F-15 based ASAT and the B-52 launched Pegasus), launch sites for light payloads (such as an ASAT) are no longer fixed, as they used to be.21

Second, and more significantly, LEO satellite orbit ground tracks are constantly being permuted by the rotation of the Earth and the variations in its gravitational field. Unless, the launch site is in very northern latitudes and unless the target satellites' orbital inclination is low, it is unlikely that any launch site would be unable to eventually attack a given target. As with co-orbital attack, the cost imposed is one of delay. We will take up this topic in more detail in Chapter 9.

Principle of Pop-up attacks in LEO and GEO: At a target height of 200 km, pop-up attackers require a ΔV 7.78 km/sec less than their targets. At 1500 km, this difference is 3.98 km/sec. At 26,560 km (SSO) this difference is 1.74 km/sec. At 42,163 km (GEO) this difference is 1.60 km/sec. Important constraint: pop-up attack launch sites must be in or close to the target’s orbital plane.

Having determined that the attacker is best served by a pop-up assault, we now take up the question of high speed impact destruction in the next chapter.

---

21 Note that only the F-15 based system launches ASAT's. The Pegasus is designed to put small satellites (350 kg) into LEO, it is not an ASAT system.
Chapter 5

Kinetic Attack

It turns out that the preferred method of killing satellites is similar to the preferred method of killing people here on Earth: punch a hole in the target with a fast moving piece of metal. In this chapter I will analyze this method in detail. Kinetic kill vehicles (KKVs) are an extremely effective form of attack. Further, the target of such an attack cannot be adequately shielded.

This chapter consists of two sections. The first deals with satellite vulnerability to hypervelocity impact. The second section evaluates the possibility of shielding the target satellite from such an attack.

5.1 Vulnerability

When assessing a new means of attack, the first question one must ask is: can the target be destroyed? This may seem a foolish question, but there are targets that are very difficult to destroy. If the target cannot be destroyed by the available means, then worrying about how to get to such a target is pointless.

The history of air power provides two good examples of effectively indestructible targets. During the Battle of Britain in World War II, the Luftwaffe bombed British radar antennas in an attempt to blind Fighter Command. Despite pin-point bombing by highly trained pilots flying at low level, the radars were off line for only a short while. The radar lattices (antennas) looked fragile, but because of their very small
surface area they were “almost immune to high explosive.”

During the Vietnam War, a key road/rail junction in North Vietnam was the Thanh Hoa bridge. Over built by the Chinese with large amounts of concrete, it was much stronger than needed, which made it very difficult to destroy. The gravity bombs available were not accurate enough and were not big enough. They were simply incapable of destroying that much concrete. Despite the best efforts of the U.S. Air Force, the bridge was never put out of action.

### 5.1.1 Hypervelocity Impacts

The targets under consideration here are satellites. The question is: are they worth attacking? Depending on the altitude of the orbit, between LEO and GEO, orbital velocities range from three to eight km/sec. If an ASAT can be placed in the path of an orbiting satellite (i.e. with zero rotational velocity with respect to the center of the Earth), then the closing velocity will be 3-8 km/sec. If the attacker is moving perpendicular to the target’s velocity at the time of impact, the closing velocity will be higher.

Impacts at these closing velocities are termed “hypervelocity impacts”, and they have some special characteristics. At these speeds a lot kinetic energy is involved, craters are formed in the front face of the target as material is melted or vaporized and ejected through to the far side of the targeted satellite.

### 5.1.2 Non-Catastrophic Collisions

Depending on the relative masses of the two colliding objects, the effects of hypervelocity impact can be divided into two types: non-catastrophic and catastrophic. In non-catastrophic collisions, a small object hits a large one. A portion of the target’s

---


<table>
<thead>
<tr>
<th>Material</th>
<th>$\gamma \left( \frac{sec}{km} \right)$</th>
<th>$\Gamma_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt</td>
<td>5</td>
<td>$50 \times \gamma v^2$</td>
</tr>
<tr>
<td>Glass</td>
<td>20</td>
<td>$60 \times \gamma v^2$</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.3</td>
<td>$20 \times \gamma v^2$</td>
</tr>
<tr>
<td>Spacecraft Structures</td>
<td>1.0</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Table 5.1: $\gamma$'s for Non-Catastrophic Collision, $\Gamma_c$'s for Catastrophic Collision


mass is violently removed as the projectile passes through it, much like a bullet fired through a door. In catastrophic collisions, two similarly sized objects collide. The entire mass of the target satellite is affected by the impact. I will assume here that the attacker is smaller than the target (for an analysis of cases where this is not true, see Section 5.2.5). If the target is much bigger than the impacting object in terms of mass ($M_{\text{attacker}} \ll M_{\text{target}}$), then the collision is non-catastrophic. The mass ejected ($M_{\text{ejected}}$) is a function of the material involved and the closing velocity ($v$):\

$$M_{\text{ejected}} = \gamma v^2 \left( \frac{km}{sec} \right) M_{\text{attacker}}$$

where $\gamma$ varies with the materials involved (See Table 5.1) and $v$ is the impact velocity in km/sec.

I am interested in the last of these numbers since I am smashing spacecraft togetherness, not asteroids. For my purposes then, the ejected mass for non-catastrophic

---

collisions is:

\[ M_{ejected} = 1.0 \times v^2 \left( \frac{km}{sec} \right) M_{attacker} \]

### 5.1.3 Catastrophic Collisions

As \( M_{attacker} \) begins to approach \( M_{target} \) however, the effects of the collision change. Beyond a certain threshold \( \Gamma_c \) the entire target begins to buckle and crack. The ejected mass then approaches the combined mass of the attacker and the target:

\[ If \, \gamma v^2 \Gamma_c > M_{target} \, then \, M_{ejected} = M_{attacker} + M_{target} \]

This threshold value is also a function of velocity and material (See Table 5.1). Unfortunately, there is no data for spacecraft structures. Because the aluminum value for \( \gamma \) is so close to that of spacecraft structures, I will assume that the \( \Gamma_c \) value for aluminum (20) also applies to spacecraft structures. In other words, if 5% of a spacecraft is suddenly and violently removed, the entire satellite is damaged.

One must be careful in applying data from sheets of aluminum to satellite structures, however. It can be argued that if a satellite’s solar panel is struck, the satellite might continue to function. The thin solar panel would provide little mass to fragment within the impact crater, and even if the entire solar panel were to buckle, damage to the satellite core could be minimal. Also solar panels degrade gracefully, if part of a panel is damaged, the rest of the panel continues to provide power. On the other hand, certain satellite structures a very sensitive to damage. A small puncture in a fuel/oxidizer tank can completely disable a satellite.\(^5\)

For purposes of this dissertation then, I will assume that a target satellite must be struck in its “core” area—that is, in the package of electronics and maneuver elements

---

\(^5\) Recently a newly launched $150 million communications satellite became a total loss when a leak developed in oxidizer container. The oxidizer tank was part of the attitude control system which keeps the satellite properly oriented towards the Earth. Without this proper orientation, the satellite is unable to perform its mission. See *Aviation Week & Space Technology*, January 7th, 1991, p. 34.
which are often surrounded by solar panels. Having done this, I think it reasonable to assume that if 5% of this core package is ripped away then the satellite will cease to function.

I can now express the target mass fraction \( (M_f) \) required to destroy a satellite as a function of closing velocity:

\[
M_f = \frac{1}{20v^2}
\]  
(5.1)

**Principle of Satellite Vulnerability:** If an ASAT can reach the core of its target with a high closing velocity \( v \) (order 3-8 km/sec), it can destroy a satellite \( 20v^2 \) times its own mass.

Applying this principle then, at 3.069 km/sec (GEO orbital velocity relative to the center of the Earth), an ASAT can destroy a satellite 188 times it's own mass. At 7.793 km/sec (LEO orbital velocity, 200 km height), an ASAT can destroy a satellite 1215 times its own mass.

**Summary**

Artificial Earth satellites are worth attacking. They can be effectively destroyed and orbital mechanics provides the attacker with a large advantage. Because of the high orbital velocities of satellites (3-8 km/sec), simply placing an object in the path of a target satellite provides enough kinetic energy to do enormous damage. Anti-satellites (ASAT's) can destroy satellites hundred's, even thousand's of times their own mass. This also means that ASAT's do not need explosive warheads to destroy their targets. In fact, the kinetic energies involved are an order of magnitude larger than the explosive power, per kilogram, of TNT.\(^6\)

\(^6\)An object traveling at 10 km/sec has a kinetic energy of 50 MJ/km, TNT has an energy yield of 4 MJ/km; See "Orbital Dev. as: an Inexpensive Countermeasure to Space Based Weapons Systems" by John R. Michener. Physics and Society Volume 16 #2, April 1987.
5.2 Target Shielding

In the previous section I established that satellites are vulnerable to kinetic attack. I now turn to the question of shielding: can satellite vulnerability to kinetic attack be countered by shielding the defender?

This section examines the feasibility of armor-plating the target satellite. There are other means of defense available such as decoys or self defense. These are discussed in Section 2.5, p. 52.

Thus far we have considered the mass of the target satellite relative to the mass required to destroy it at LEO and at GEO orbital velocities. Shielding may improve this ratio (from the defender's point of view) by increasing the mass required to destroy the target. However, shields also add mass to the target. The question is whether or not adding shielding ever improves this ratio, and if so, under what circumstances.

5.2.1 Shielding Requirements

Precise data for shielding objects from hypervelocity impacts is difficult to come by. Most of my information comes from the technical debate over whether or not a man-made debris belt can be used to destroy a “star wars” system of laser battle stations. Authors on opposite sides of this issue do agree that shielding requirements are based on areal densities, as in kilograms per square-meter (kg/sq-m).

Can shields be constructed to stop a projectile arriving at up to 10 km/sec? Yes. Using studies of how to protest manned missions in orbit from debris impact, John Michener has been able to derive the requirements for a “harmonic shield.”

At impact velocities of 10 km/sec, a shield with an areal density 0.75 times that of the attacking object is required to defend the target. What follows is a more detailed explanation of the harmonic shield.

In its simplest form, the shield consists of two plates, a thinner front plate which

---

7Michner, John R., “Orbital Debris: an Inexpensive Countermeasure to Space Based Weapons Systems,” Physics and Society, Vol 16 #2, April 1987, p. 10. The detailed analysis comes from a draft of this paper, not all of which appears in the final publication.
is struck first, and a second, thicker back plate which is struck second. Here is how
the shield works: As the projectile strikes the first shield, it is disrupted. The thin
shield makes use of the same principle of ejected mass multiplication. That is the
mass of the thin shield in the area of impact can fragment and disrupt a mass much
larger than its own. The vaporized and fragmented projectile, along with some front
shield mass comes through the far side of the first shield. This mass is now moving
slower and spreads out as it moves between the gap between the two shields. This
mass then strikes the back plate over a large area. The back plate is designed to be
thick enough to contain the impact of these smaller and slower particles.

In order to contain a projectile moving at 10 km/sec, the front shield should be
0.25 the areal density of the projectile, and the back plate should be roughly twice
the density of the front plate. The spacing between the two plates should be 100
times the thickness of the first plate. Thus, the shield should be a total of 0.75 times
the areal density of the projectile.

We can make this shield effective against range of projectiles by dividing the front
plate into two plates, one one half as thick as the other, and spacing them apart. We
have now constructed a thinner shield out first plate of the larger shield. We can then
repeat the process with the new front plate. In this way the shield can be made to
contain less dense projectiles without adding an mass (and just a little spacing) to
the shield. That is, it can now stop a range of projectile areal densities, limited only
by the thickness of the last back plate.

5.2.2 Satellite Characteristics

We have a shield which is effective at 10 km/sec. How much shielding is required at
lower velocities. I assume that this shield thickness requirement scales linearly with
kinetic energy. That is, that the thickness of the shield varies as the square of the
impact velocity. Given that the thickness requirement at 10 km/sec is 0.75 the areal
density of the impacting object, I can deduce the requirement at lower velocities. The
<table>
<thead>
<tr>
<th>Impact Velocity</th>
<th>Relative Density</th>
<th>Shield Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 km/sec</td>
<td>0.750</td>
<td>256 kg/m²</td>
</tr>
<tr>
<td>LEO Orbital Velocity: 7.793 km/sec</td>
<td>0.455</td>
<td>156</td>
</tr>
<tr>
<td>GEO Orbital Velocity: 3.069 km/sec</td>
<td>0.094</td>
<td>32.1</td>
</tr>
</tbody>
</table>

Table 5.2: Relative Shield Thickness Requirement

resulting equation is:

$$Relative - Density = 0.75 \times \frac{v^2}{100}$$

Where \( v \) is in km/sec.

This equation is confirmed by one data point. An Air Force study, of shielding requirements found that at 7 km/sec, a relative density of at least 50% was required to stop the projectile.\(^8\) If we plug 7 km/sec into the above equation and use the higher 1.0 value, we get 49%. Thus, we have some confidence that the above equation represents at least a lower bound on required shield density. That is, this assumption may underestimate the shield mass required, but it will not overestimate it.

Applying this equation gives us the first two columns of Table 5.2. For this table I chose the orbital velocities for GEO and LEO orbits because they would be the impact velocities during a pop-up attack at those orbital altitudes. We know from Chapter 4 that the pop-up attack is the most efficient form of attack.

I will also assume, since most satellite cores are ball-like, that the satellite can be modeled as a sphere. This means that the shield must be a half sphere-shell, with an inner radius at least equal to that of the satellite sphere.

I assume a half sphere because the ASAT may not have a zero velocity when it reaches the target. We assume a minimum energy pop-up attack with zero velocity relative to the Earth when the satellite impacts with the ASAT. But an attacker

\(^8\)Brewer, E.D.; Hendrich, W.R.; Thomas, D.G.; and Smith, J.E.; “Shield design, analysis, and testing to survive stainless steel projectiles,” Oak Ridge National Laboratory, TN (USA), January 1990, Technical Report Number ORNL/TM-11381. They used a 1.75 gm cylindrical projectile whose length equalled its diameter. The projectile diameter was 0.666 cm (Table 4, p. 13) or a radius of 0.333 cm. This gives the projectile an area of \( \pi \times 0.33^2 = 0.35 \text{cm}^2 \). The areal density is therefore 1.75gm/0.35cm² = 5gm/cm². The shields used were all at least 2.5gm/cm² (Table 1, p. 7) or 50% the areal density of the projectile.
might not chose a minimum energy attack. For example, if the attacker wanted to
shorten the ASAT ascent time in order to prevent her target from deploying decoys,
she would use a larger rocket than needed; the ASAT could be traveling upwards at
several kilometers per second at the point of impact. Therefore, I assume that an
impact will not necessarily be head on. In order to shield against an ASAT which
might not attack with a minimum energy pop-up trajectory, I require a half-sphere.

By ignoring the solar panels and antennas of the target satellite, I considerably
reduce the size of the shield required. This is an assumption which is of considerable
benefit to the defender.

Since the satellite is moving in orbit at a considerable speed, if the attacker ex-
ecutes a pop-up attack, then only a half sphere-shell will be required to shield it.
Thus, if the satellite is of radius $R$, then the shield must have an area of at least:

$$\frac{1}{2} \times 4\pi R^2 = 2\pi R^2$$  \hspace{1cm} (5.2)

Unshielded destruction of a satellite is expressed in terms of mass, but shielding
requirements are based on satellite area. I need to be able to relate the two. Fortu-
nately, surveys of satellite size vs area have been conducted.$^9$ The authors concluded
that the following relationship summarized the data:

$$Mass = 62 \times Area^{1.13}$$  \hspace{1cm} (5.3)

where $Mass$ is the mass of the satellite in kilograms (kg) and $Area$ is the cross sectional
area in square meters.

$^9$Kessler, Donald J. and Cour-Palais, Barton G. "Collision Frequency of Artificial Satellites:
Creation of a Debris Belt" in *Space Systems and their Interactions with Earth's Space Environment*,
edited by Garret, Henry B. and Pike, Charles P. American Institute of Aeronautics and Astronautics,
New York, 1980. p.719 Another survey claims that the correct relation is $M = 64A^{3/2}$ which is very
close to the one we are using. See Wertz, Table 10-25, p. 287.
5.2.3 ASAT Mass

Currently, the only fully tested high speed interceptor in the world is the F-15 based Miniature Homing Vehicle (MHV) ASAT system. So I use it as a typical ASAT model. It is cylindrical with a radius of 15.25 cm (6 inches)\(^{10}\) and it weighs 25 kg.\(^{11}\) This gives it an areal density of 342 kg/m\(^2\). The necessary shield densities to protect against this ASAT for various impact velocities can be computed based on relative density shielding requirements. The results are shown in the third column of Table 5.2.

Before the program was canceled, its developers estimated that they could shrink this package down to 4.5 kg.\(^{12}\) Recently, Star Wars researchers have developed a 5 kg interceptor,\(^{13}\) although it has yet to be tested in space.

I will use 4.5 kg as a model for future ASATs and consider the defender advantages versus it as well. I assume that the areal density of the future ASAT would be the same as the that of the larger version, so the third column of Table 5.2 applies to this system as well.

5.2.4 Shield Masses

I now have enough pieces to determine shield masses for typical satellites of various radii and at various impact velocities. The results are shown in Table 5.3. Assuming that the satellite core is a sphere, I can use the radius to estimate the cross sectional area. Equation 5.3 allows me to compute the satellite mass from its area. The shield area can be computed from Equation 5.2. Using shield area and the shield densities from Table 5.2, I can compute the required shield mass at a 10 km/sec impact velocity, LEO orbital velocity, and GEO orbital velocity. Note that the shield masses in all cases are larger than the ASAT mass.


\(^{12}\)Jasani, p.16

<table>
<thead>
<tr>
<th>Satellite Radius</th>
<th>Satellite Area</th>
<th>Satellite Mass</th>
<th>Shield Area</th>
<th>Shield Mass at:</th>
<th>10 km/sec</th>
<th>LEO</th>
<th>GEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{1/\pi}$ m</td>
<td>1 m$^2$</td>
<td>62 kg</td>
<td>2 m$^2$</td>
<td>512 kg</td>
<td>312 kg</td>
<td>62.4 kg</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.14</td>
<td>226</td>
<td>6.28</td>
<td>1608</td>
<td>980</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>$\sqrt{10/\pi}$</td>
<td>10</td>
<td>836</td>
<td>20</td>
<td>5120</td>
<td>3120</td>
<td>624</td>
<td></td>
</tr>
<tr>
<td>$\sqrt{100/\pi}$</td>
<td>100</td>
<td>11282</td>
<td>200</td>
<td>51200</td>
<td>31200</td>
<td>6240</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>314</td>
<td>41108</td>
<td>628</td>
<td>160768</td>
<td>97968</td>
<td>20159</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3: Shield Masses for Satellite Radii vs Impact Velocity

5.2.5 Attacker Advantages

Next I calculate the attacker advantage versus unshielded targets. The results are shown in Table 5.4. The rows (which correspond to satellite sizes and masses) of Tables 5.4 and 5.5 correspond to the rows of Table 5.3. The "attacker advantage" represents the ratio of target mass to mass required for an unshielded kill.

Although the equations above state that a 62 kg target can be destroyed by a 0.051 kg ASAT at LEO orbital velocity, ASAT's don't come that small.\textsuperscript{14} The mass of an ASAT warhead represents a lower bound on attacker mass. This limits the attacker advantage when hitting small targets. I would argue that there are two limits. Currently that limit is 25 kg, the current smallest ASAT. In the future it should shrink to 4.5 kg, the projected miniaturized version of that ASAT. Both attacker masses are listed in the table. Note that as the target mass increases, the attacker advantage reaches the projected limit for LEO and GEO orbital impact velocities: 1215 and 188, respectively (see Section 5.1.3, page 157).

These results can now be compared with the attacker advantages for shielded satellites. The shield masses in Table 5.3 represented the mass necessary to just stop the attacker.

What about counter-countermeasure? The attacker could place a smaller impact shield in front of her interceptor with an equal or greater density and spacing than the capable of 10 g's of acceleration and a total $\Delta V$ of 1 km/sec.

\textsuperscript{14}KKV's require constant corrections up to the moment of impact. Thus, the minimum size of the maneuver/sensor package determines the minimum ASAT mass. Sub-munitions are not possible in this context.
<table>
<thead>
<tr>
<th>Satellite Mass</th>
<th>Mass Required for an Unshielded Kill at:</th>
<th>Attacker Advantage with:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEO</td>
<td>GEO</td>
</tr>
<tr>
<td>62 kg</td>
<td>0.051 kg</td>
<td>0.330 kg</td>
</tr>
<tr>
<td>226</td>
<td>0.186 kg</td>
<td>1.20 kg</td>
</tr>
<tr>
<td>836</td>
<td>0.688 kg</td>
<td>4.45 kg</td>
</tr>
<tr>
<td>11282</td>
<td>9.28 kg</td>
<td>60.0 kg</td>
</tr>
<tr>
<td>41108</td>
<td>33.8 kg</td>
<td>219 kg</td>
</tr>
</tbody>
</table>

Table 5.4: Attacker Advantages for an Unshielded Target

<table>
<thead>
<tr>
<th>Satellite Mass</th>
<th>Target Mass (Satellite + Shield) at LEO</th>
<th>Target Mass (Satellite + Shield) at GEO</th>
<th>Attacker Advantage with:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEO</td>
<td>GEO</td>
<td>43.7 kg warhead</td>
</tr>
<tr>
<td>62 kg</td>
<td>374 kg</td>
<td>124 kg</td>
<td>8.56</td>
</tr>
<tr>
<td>226</td>
<td>1206 kg</td>
<td>428 kg</td>
<td>28.0</td>
</tr>
<tr>
<td>836</td>
<td>3956 kg</td>
<td>1460 kg</td>
<td>90.6</td>
</tr>
<tr>
<td>11282</td>
<td>42482 kg</td>
<td>17522 kg</td>
<td>972</td>
</tr>
<tr>
<td>41108</td>
<td>139076 kg</td>
<td>61267 kg</td>
<td>3183</td>
</tr>
</tbody>
</table>

Table 5.5: Attacker Advantages for an Shielded Target

target’s shield. On impact, both shields would be vaporized in front of the attacking warhead, spreading their mass outwards, allowing the interceptor to continue on to destroy the target.

The effects of the impacting shields is propagated in both directions. As the two first thin layers meet, they vaporize each other, sending debris in both directions, all of which is contained by the second layers of each of the shields. Then the second layers impact, repeating the process. At the end, both of the back plates meet and disrupt each other. Assuming that there is spacing between the back plates and their respective ASAT and satellite, this dispersed mass will not be enough to either to disrupt both the satellite and the ASAT or too little, in which case the ASAT will continue on to disrupt the satellite.

Since the attacker doesn’t know the exact density of the defender’s shield, I assume that the attacker uses the largest density in Table 5.2: 256 kg/m². For the 25 kg interceptor, this shield would be \( \pi (0.1525m)^2 \times 256kg/m^2 = 18.7kg \), bringing the total interceptor mass to 43.7 kg. I assume that the 4.5 kg interceptor would have the same areal density as the larger one. The smaller interceptor’s total mass (shield
and warhead) would therefore be the same relative mass (1.75 times) as the larger one, giving the smaller interceptor a total mass of $4.5kg \times 1.75 = 7.87kg$, including the shield.

Using the shield masses calculated in Table 5.2, I can now calculate the attacker advantage for shielded targets. The results are shown in Table 5.5. Comparing the attacker advantages of Table 5.4 with those of Table 5.5, we see that in every case the shielded satellite offers the attacker a better attacker advantage. Note that the results for a 10 km/sec impact velocity is not shown in the attacker advantage tables. But since attacker advantages increase with impact velocity, I can safely conclude that these effects are even more pronounced at higher impact velocities.

From the defender's viewpoint then, shielding is useful only as long as the attacker does not counter it. As soon as the attacker uses a counter shield, the defender's shielding turns into a disadvantage.

What advantage might the defender might derive if the attacker under estimates the extent of the satellite's shielding? Under these circumstances the satellite would survive a single ASAT attack. But in order to do this, the defender would have to invest large amounts to fly very heavy shields. The attacker, once his initial attack failed, could simply attack again, until the shield was destroyed. Or, if possible, the attacker, could use a thicker and heavier shield on subsequent attacks. Or, the attacker could insert a high-density rod into the ASAT to increase the areal density of a small portion of the ASAT which would penetrate the shield.

Thus, even if the defender out-guesses the attacker, she gains very little. The attacker will simply have to expend more than one ASAT to kill the target. The shield/counter-shield war denies the attacker the kinetic kill relative mass advantage since the attacker must use a shield of equal areal mass to penetrate the defender's shield. But the attacker needs to only shield the smaller ASAT warhead, while the attacker needs to shield the entire satellite. Also, the advantages of pop-up attack still apply. And, of course the defender's shields must be flown on all satellites, whether or not there is a war. The attacker need only expend more ASATs, or upgrade his ASATs on the ground, in time of war. The attacker's advantage is diminished by
satellite shielding but attacker advantages remain.

There are also some problems with bumper type shields. One author claims that they are not effective for particles greater than one milligram in mass or greater than a centimeter in size. He also claims that double layered shields, while effective at impact speeds of 5-12 km/sec, do not stop particles moving slowly. apparently, at speed less than 5 km/sec, the first wall does not sufficiently disrupt and disperse the projectile for the second wall to contain the impact.\(^{15}\)

5.2.6 Summary

The result of this investigation into shielding is that shielded satellites remain vulnerable targets. If the attacker is aware that the defender is shielding his satellites and can counter it, then the attacker derives a greater advantage than before defender shields were added.

If the attacker is unsure whether his targets are shielded, other options remain open. By incurring the cost of increasing the interceptor mass by a factor of 1.75, the attacker can assure a kill against a large range of shield densities. If the attacker still cannot penetrate the shield, a number of follow on attacks will be needed, depending on the thickness of the defender's shield, but this still gives the attacker an advantage.

In sum then, the shield/counter-shield game is a losing proposition for the defender in almost all foreseeable circumstances.\(^{16}\) The defender should not bother to shield his satellites.

Another valuable insight that follows from this analysis is that small satellites provide a much lower attacker advantage because the interceptor mass is bounded at the lower end. Table 5.4 represents a more realistic set of attacker advantages. In the worst case for the attacker (attacker shields her interceptors, defender does not), the attacker advantages in Table 5.4 are reduced by a factor of 1.75.

---


\(^{16}\) The only case where shielding makes sense is if the defender knows years in advance of any war the areal density of the attacker's ASATs, the attacker has limited ASATs, and the attacker cannot modify her ASATs. Only under highly unlikely circumstances is shielding a good idea.
Having determined the effects of collision at high speed, I now consider the cost of getting an ASAT to the target satellite. For this, we turn to a discussion of rockets.
Chapter 6

Rockets

In Chapter 4 we compared $\Delta V$'s of attacker and target. But what I am really interested in is the actual size and cost the rockets required to achieve these changes in velocity. I begin by examining ideal rockets. Ideal rockets consist entirely of fuel and payload, their engines and structure are assumed to be weightless. Later I will add engines and structure with realistic weights. Then I will introduce gravity losses incurred by all rockets as they leave the surface of the Earth. With this rocket model will be able to translate the $\Delta V$'s and payloads of the previous section into rocket masses required to launch targets and to intercept them.\textsuperscript{1} Finally, we will use a survey of existing rockets to construct a cost model for a range of mission requirements.

6.1 Ideal Rockets

Rockets are based on the principle of conservation of momentum. The rocket propellant (fuel) is ignited and ejected as exhaust gas from the bottom of the rocket. This produces a Newtonian reaction moving the rocket upward. The mass times the exit velocity of the propellant ($v_e$) downward equals the mass of the remaining rocket times it's change in velocity upward.

If one could burn all the propellant instantly, this simple equation would describe the change in velocity a particular rocket was capable of. Unfortunately, this is not possible: rockets take finite time to burn. This burn time ($\tau_b$) for large rockets is measured in seconds. A long burn time is 300 seconds or 5 minutes.

Because the fuel takes non-zero time to burn, the rocket must accelerate the as yet un-burned propellant as well as the payload. Consequently, the relationship of rocket size to $\Delta V$ is not linear.

The size of a rocket is measured in terms of its mass ratio ($R_m$). This is the ratio of the initial mass of the rocket ($M_0$) to the mass of the rocket at burn-out ($M_{\text{final}}$). Thus,

$$R_m = \frac{M_0}{M_{\text{final}}}$$

In an ideal rocket, $M_{\text{final}}$ is the same as the mass of the payload ($M_{\text{pay}}$). The difference between $M_0$ and $M_{\text{final}}$ is the propellant mass $M_{\text{prop}}$. The rocket equation for change in velocity for an ideal rocket is $^2$:

$$\Delta V = v_e \times \ln\left(\frac{M_0}{M_{\text{final}}}\right)$$

or

$$e^{\Delta V/v_e} = \frac{M_0}{M_{\text{final}}}$$

Where $v_e$ is exhaust velocity, $M_0$ is the rocket mass before the burn, and $M_{\text{final}}$ is the rocket mass after the burn.

This equation yields some very interesting results. First, $\Delta V$ is not linearly related to the rocket mass ratio, the relationship is exponential. That is, doubling the $\Delta V$ requires the mass ratio to be increased to the square of the original mass ratio. For example, if the mass ratio were 10 ($\frac{1}{10}$ of the rocket mass is payload), to double the

---

$\Delta V$ would require a mass ratio of 1%, an order of magnitude decrease in payload. To achieve this higher $\Delta V$ for a fixed payload would require a rocket which was 10 times larger. The mass ratio, however, does increase linearly with the payload mass. Double the payload mass and the rocket size simply doubles.

*Principle of rocket mass: the total mass of a rocket varies linearly with payload mass, but exponentially with the $\Delta V$ required.*

### 6.1.1 Specific Impulse

An important measure of a rocket's performance is its specific impulse ($I_{sp}$). This quantity relates to exit velocity, acceleration ($N_g$; number of G's of acceleration) and burn time. Here are some useful equations: ³

$$I_{sp} = \frac{v_e}{g}$$

$$\tau_b = \frac{M_{prop}}{M_0} \times \frac{I_{sp}}{N_g} \quad (6.1)$$

Since $\frac{M_{prop}}{M_0}$ is less than one in chemical rockets (although often the vast majority of weight in a chemical rocket is propellant), and since $N_g$ must be greater than one if the rocket is to get off the ground, one can see from Equation 6.1 that the burn times will always be less than the specific impulses (measured in seconds).

This also provides the very useful limit:

$$\tau_b < \frac{I_{sp}}{N_g}$$

This relates burn time and acceleration to specific impulses when the rocket mass is mostly propellant.

Typical $I_{sp}$ values are 180 to 280 seconds for solid fueled rockets, and 270 to 470 seconds for liquid fueled rockets.⁴ Since we are looking toward the future of space, I will assume that liquid rockets have an $I_{sp}$ of 470 and solid rockets have an $I_{sp}$ of 280

³M.I.T. Course Notes, 16.53 Rocket Propulsion, Fall, 1989, taught by Prof. Hastings, pp. 3-4.
⁴M.I.T. Course Notes, 16.53 Rocket Propulsion, Fall, 1989, taught by Prof. Hastings, p. 5.
6.2 Non-Ideal Rockets

In the real world, rockets do not consist simply of payload and propellant. The rocket engine and, more significantly, the rocket structure add significant weight to the rocket. This structural weight is largely dependent on the amount of propellant being contained. Thus, the structural weight of the rocket is proportional to the weight of the propellant ($M_{\text{prop}}$). This proportion, called the "Tankage Factor" ($T_f$) is typically 10% in solid rockets, and 15% in liquid ones. In comparison, the weight of the engine is small, typically 2% of the initial weight ($M_0$) of the rocket.\(^6\)

The burn out mass ($M_{\text{final}}$) of the rocket previously consisted only of payload. Now it is the sum of the payload mass ($M_p$), the structural mass ($M_s = [0.10 or 0.15] \times M_{\text{prop}}$), and the engine mass ($M_e = 0.02 \times M_0$).

Basically, all of these factors eat away at the amount of payload carried. What I really want to know is the ratio of payload mass to initial mass, the "payload percentage." With the ideal rocket this was $\frac{1}{R_m}$, but now it is:

$$\text{Payload\%} = \frac{M_p}{M_0} = \frac{1}{R_m} - T_f \times (1 - \frac{1}{R_m}) - 0.02$$  \hspace{1cm} (6.2)

These factors impose a limit on the rocket's performance. Even if there is no payload, the best mass ratio is limited by the fact that 2% of $M_0$ goes to the engine and 15% or 10% of $M_{\text{prop}}$ goes to structure. By setting $\frac{M_p}{M_0}$ to zero in the above equation and solving, we can see that the best mass ratio available is 9.166 for solid rockets, and 6.76 for liquid rockets. By plugging these limits into the rocket equation, I can derive maximum $\Delta V$ possible for chemical rockets.

**Principle of limits of chemical rockets:** The maximum $\Delta V$ possible with a single stage solid rocket with an $I_{sp}$ of 280 sec is 6.080 km/sec. The maximum $\Delta V$ possible

---

\(^6\)NASA publication, "Spacecraft Propulsion Systems — What They Are and How They Work" by Robert H. Frisbee, p.4

\(^6\)M.I.T. Course Notes, 16.53 Rocket Propulsion, Fall, 1989, taught by Prof. Hastings, p. 17.
with a single stage liquid rocket with an $I_{sp}$ of 470 is 10.25 km/sec.

The lower tankage factor is an advantage that the solid rockets have over the liquid ones. But it is not enough to compensate for the lower solid rocket specific impulse. Overall, liquid rocket performance is greater, but there are good reasons to use solid rockets. Solid rockets can be ready to launch with very little notice because the fuel can remain in the rocket for years. Liquid fueled rockets require advanced preparation and cannot be kept ready for launch for extended periods because their fuels are volatile, corrosive, or require extensive cooling. Liquid rockets are typically more expensive and complex to build. Liquid rocket reliability is roughly 90%, while solid rocket reliability is 95%.

6.2.1 Staging

One way to overcome these performance limits is to stage the rocket. That is, use one rocket to carry another smaller rocket to be ignited when the first rocket burns out. In effect, this means throwing overboard the fuel tanks and structural elements once the fuel they originally contained has been burned. This reduces the loss associated with structural mass because not all of it is accelerated with the payload.

Ideally, one would want to have an infinite number of stages. That way structural mass could be disposed of as soon as the rocket was done with it. But engineering constraints require that staging be done in discrete elements. Each stage also requires a new engine which adds a cost per stage. Staging also suffers from diminishing returns, that is, each additional stage provides much less benefit than the previous stage. Consequently, few rockets have more than three stages. But those three stages can recover about half the losses of a single stage rocket as compared to an ideal rocket. In our model I will assume that three stages are used.

When allocating the workload for each stage, I will assume that each stage con-

---

8M.I.T. Course Notes, 16.53 Rocket Propulsion, Fall, 1989, taught by Prof. Hastings, p.17.
<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Expected Time in Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>158</td>
<td>0.5 days</td>
</tr>
<tr>
<td>186</td>
<td>3 days</td>
</tr>
<tr>
<td>278</td>
<td>35 days</td>
</tr>
<tr>
<td>300</td>
<td>36 to 146 days</td>
</tr>
<tr>
<td>371</td>
<td>200 days</td>
</tr>
<tr>
<td>400</td>
<td>183 to 1461 days (0.5 to 4.0 years)</td>
</tr>
<tr>
<td>500</td>
<td>2 to 35 years</td>
</tr>
<tr>
<td>557</td>
<td>11 years</td>
</tr>
<tr>
<td>600</td>
<td>80 to 190 years</td>
</tr>
<tr>
<td>700</td>
<td>25 to 400 years</td>
</tr>
<tr>
<td>800</td>
<td>75 to 1000 years</td>
</tr>
</tbody>
</table>

Table 6.1: Approximate Orbital Lifetimes


tributes an equal ΔV. This makes computation easier, and more important, it is the optimal allocation of workloads.10

6.2.2 Gravity Losses

Another source of loss for a rocket is gravity. Because satellites must be high enough to avoid atmospheric drag, rockets must go up as well as imparting horizontal velocity. If the satellite orbit is to last days rather than hours, is should be at least 200 km above the surface of the earth, as Table 6.1 shows. The U.S. "Big Bird" broad coverage photo reconnaissance satellite orbit dips as low as 161 km, with an apogee of 250 km.11 We’ll use 200 km as a minimum satellite altitude.

If there were no atmosphere, rockets could be launched horizontally and all of

---


their energy would go into satellite orbital velocity. But vertically launched rockets must struggle against the forces of gravity. If a rocket has equal to or less than one G of acceleration, the rocket will never leave the pad and the gravitational losses will be 100%.

Basically, during the entire time of burn \((\tau_b)\) in vertical flight, the \(\Delta V\) obtained is being drained by the force of gravity. The total \(\Delta V\), assuming that the force of gravity does not change appreciably during the burn, is:\(^{12}\)

\[
\Delta V = v_e \times \ln(R_m) - g \times \tau_b
\]

The second term represents the gravity loss. Thus, the shorter the burn time the fewer the losses. Unfortunately, atmospheric drag is highest at low altitudes. Consequently, rocket designers must trade off these two effects to achieve an optimum result. My model does not include atmospheric drag on the rocket, but I will keep my \(\tau_b\)'s realistic.

6.2.3 Vertical Height with Gravity Losses

Thus far, I have an expression for the loss of velocity due to gravity losses. But I am interested in the \(R_m\) needed to reach 200 km altitude, after gravity losses. To do this I need an expression that integrates the velocity change over time to provide height.

The height at burn out \((H_b)\) can be derived by taking the \(\Delta V\) equation with gravity losses, and integrating it assuming a constant rate of fuel consumption. The result is:\(^{13}\)

\[
H_b = \frac{-v_e \tau_b \ln(R_m)}{R_m - 1} + v_e \tau_b - \frac{1}{2} g \tau_b^2
\]

The last term represents the gravity loss. Now I need to compute the maximum height attained. After the rocket burns out, it coasts upward, converting velocity

\(^{12}\)M.I.T. Course Notes, 16.53 Rocket Propulsion, Fall, 1989, taught by Prof. Hastings, p. 9.

\(^{13}\)M.I.T. Course Notes, 16.53 Rocket Propulsion, Fall, 1989, taught by Prof. Hastings, p. 10.
into altitude (with no losses if we ignore aerodynamic drag) as it decelerates. I want to know the height it finally reaches. This is because I want to determine the minimum $\Delta V$ needed to reach 200 km. The velocity at burn out ($V_b$) can be computed using the $\Delta V$ equation above. The maximum height reached by the vertically fired rocket is:

$$H_{\text{max}} = H_b + \frac{V_b^2}{2g}$$

Substituting in and combining terms, we get:

$$H_{\text{max}} = \frac{v_b^2(lnR_m)^2}{2g} - v_e\tau_b\left(\frac{R_m}{R_m - 1}lnR_m - 1\right)$$  \hspace{1cm} (6.3)

The last term represents the gravity loss. Trying various values, I find that an $R_m$ of 2.22 yields an $H_{\text{max}}$ of 200 km.

### 6.3 The Cost of Reaching 200 km

I can now use the Equation 6.3 to determine the cost of reaching 200 km height. That cost will be expressed in terms of the amount of payload that can be carried as a percentage of initial rocket weight ($\frac{M_{\text{payload}}}{M_0}$), what I call the “payload percentage.”

Assumptions:

- $I_{sp} = 470$ seconds, max liquid fueled performance.
- $\tau_b = 235$ seconds, order 2 G’s at lift-off.
- $v_e = I_{sp} \times 9.8 = 4.606$ km/sec.
- $T_f = 15\%$.
- Engine Weight = 0.02 $\times M_0$.

---

14 M.I.T. Course Notes, 16.53 Rocket Propulsion, Fall, 1989, taught by Prof. Hastings, p. 10.
15 M.I.T. Course Notes, 16.53 Rocket Propulsion, Fall, 1989, taught by Prof. Hastings, p. 11.
From the above equation I know that in order to reach an $H_{\text{max}}$ of 200 km, a $R_m$ of 2.22 is required. If this were an ideal rocket, I could compute the percentage simply by dividing into 1: $\frac{1}{R_m} = 45\%$. But I have structural and engine weight costs to pay. For a single stage, I can use the Payload\% equation (see Equation 6.2, page 172), plugging in the $R_m$ value, to get the more realistic figure of 34.8\%.

I can use staging however to improve the performance. To do this, I compute the total $\Delta V$ needed (including gravity losses) to reach 200 km. $ln(R_m) \times v_e = 3.673 \text{km/sec}$.

We can check this result with the knowledge that aerodynamic and gravity losses are typically 1.5 to 2.0 km/sec for launch vehicles.\textsuperscript{16} The potential energy needed per kg to reach 200 km from the surface of the Earth is $\frac{\mu}{(\text{Earth Radius} - (\text{Earth Radius})+200\text{km})} = 1.900 \text{MJ/kg}$. We can use Equation 4.12 (page 150) to get the velocity 1.94 km/sec. Adding in the typical losses of 1.5 to 2.0 km/sec, we get a range of 3.45 to 3.95 km/sec. This brackets our calculation nicely.

Now I divide the task into three stages, each of which will accomplish $\frac{1}{3}$ of the $\Delta V$ needed (1.224 km/sec). Each will burn for $\frac{1}{3}$ of the burn time (78.33 sec) so that the total gravity loss will be the same. Each stage carries all the subsequent stages as payload and each has the same $\frac{M_{\text{max}}}{M_0}$ ratio. Each stage has the same $v_e$, $T_f$, and engine weight as the single stage rocket. Thus,

$$R_m = e^{\Delta V/v_e} = 1.304$$

I now plug this $R_m$ into the payload equation (6.2) and get 71.15\%. Next I multiply the percentages of all the stages together to get the overall payload percentage. Since the percentage for each stage is identical, I can simply cube the result to reach 36.06\%. Not as good as the ideal rocket, but better than the single stage rocket.

Note that the percentage for a two stage rocket is 36.25\%, actually better than one with three stages. This clearly illustrates the diminishing value of staging. Almost

all the benefit of staging is actually obtained by going from one to two stages; and in this case, the marginal utility of going from two to three stages is actually outweighed by the cost of a third engine. I will, however, use the three stage model for reasons stated immediately below.

The reader will note that in this and the next section I will use six stages to reach LEO. Because I model the launch trajectory as moving up to 200km and then thrusting horizontally to achieve orbit, each leg uses a three stage rocket. In reality, both functions are accomplished simultaneously by a single rocket with three stages. Thus, my two three stage rockets are simplified model of a single three stage rocket. This breakdown is also helpful because the pop-up ASAT mission requires the altitude, but not the velocity. By breaking down the mission into these two components, it is much easier to compare the costs of the two missions (ASAT vs LEO insertion).

We can also compute the ascent costs for a solid booster using a $I_{sp}$ of 280 seconds and a tankage factor of 10%. Each of the three stages has a payload percentage of 58.41%, for a cube product of 19.9%.

### 6.3.1 Horizontal Acceleration Cost

Once a satellite is at 200 km, it needs to develop enough horizontal velocity to maintain a circular orbit. That velocity is $\sqrt{\frac{\mu}{R}} = 7.793 \text{ km/sec}$, where $R$ is the radius from the center of the Earth.

If I use a three stage liquid fueled rocket model, identical to the one used above, I can determine the payload percentage of a rocket accelerating to 7.793 km/sec horizontally (with no gravity losses). A single stage rocket would need an $R_m$ of 5.43. This translates into a payload percentage of 4.18%.

I now try with a three stage rocket. Each must accelerate to a $\Delta V$ of $\frac{7.7928}{3} = 2.603 \text{ m/sec}$. The $R_m$ for each stage is 1.76, which in turn translates to a payload percentage of 48.4%. To get the overall rocket performance, I cube this result, to get 11.36%. Unlike the previous example, staging makes a considerable difference in this case. This is because of the much larger $\Delta V$'s involved.

If I use a three stage solid fueled rocket, the costs are higher. But in a military
<table>
<thead>
<tr>
<th>Mission</th>
<th>$\Delta V$ Required</th>
<th>Number of Stages</th>
<th>Payload % (Liquid)</th>
<th>Payload % (Solid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface to 200 km</td>
<td>3.67 km/s</td>
<td>3</td>
<td>36.2%</td>
<td>19.9%</td>
</tr>
<tr>
<td>200 km to LEO</td>
<td>7.78</td>
<td>3</td>
<td>11.4%</td>
<td>2.89%</td>
</tr>
<tr>
<td>Surface to LEO</td>
<td>11.4</td>
<td>3 (6 combined)</td>
<td>4.12%</td>
<td>0.575%</td>
</tr>
<tr>
<td>LEO to GTO</td>
<td>2.46</td>
<td>1</td>
<td>50.4%</td>
<td>32.9%</td>
</tr>
<tr>
<td>GTO to GEO</td>
<td>1.48</td>
<td>1</td>
<td>66.4%</td>
<td>52.1%</td>
</tr>
<tr>
<td>LEO to GEO</td>
<td>2.46 &amp; 1.48</td>
<td>2</td>
<td>33.5%</td>
<td>17.1%</td>
</tr>
<tr>
<td>LEO to ULTO</td>
<td>0.342</td>
<td>1</td>
<td>89.8%</td>
<td>85.1%</td>
</tr>
<tr>
<td>ULTO to ULEO</td>
<td>0.327</td>
<td>1</td>
<td>90.1%</td>
<td>85.6%</td>
</tr>
<tr>
<td>LEO to ULEO</td>
<td>0.342 &amp; 0.327</td>
<td>2</td>
<td>80.9%</td>
<td>72.9%</td>
</tr>
<tr>
<td>LEO to STO</td>
<td>2.07</td>
<td>1</td>
<td>56.4%</td>
<td>39.7%</td>
</tr>
<tr>
<td>STO to SSO</td>
<td>1.43</td>
<td>1</td>
<td>67.3%</td>
<td>53.3%</td>
</tr>
<tr>
<td>LEO to SSO</td>
<td>2.07 &amp; 1.43</td>
<td>2</td>
<td>37.9%</td>
<td>21.2%</td>
</tr>
</tbody>
</table>

**Table 6.2: Payload Percentages for Various Missions**

environment, where reliability, storability and quick reaction time are important, it is likely that the solid boosters will play a large role.

A high performance solid booster will have an $I_{sp}$ of 280 sec, a $v_e$ of $9.8 \times 280 = 2744 \text{m/sec}$ or 2.744 km/sec. I can ignore the $\tau_b$ since I have no gravity losses to contend with.

A single stage rocket cannot achieve this $\Delta V$, but a staged one can. The $R_m$ for each stage is 2.58. The payload percentage is 30.7%. This result cubed is 2.89%, a much lower figure than the liquid rocket.

We can now multiply these payload percentages together to produce the results in Table 6.2. We can check these results using data from existing boosters. For liquid rockets, the payload percentage to LEO is $36.2\% \times 11.4\% = 4.12\%$. The latest Japanese liquid fueled booster under development, the H-2, has a launch weight of 179
240,000kg\textsuperscript{17} and a payload capacity of 9,020kg to a 200km LEO orbit.\textsuperscript{18} That comes to a payload percentage of 3.76%, so our calculation is certainly reasonable. The solid rocket LEO mission has a payload percentage of $19.9\% \times 2.89\% = 0.575\%$. The Titan II’s solid booster has a launch weight of roughly 279,909kg.\textsuperscript{19} and a LEO payload of 2,310kg\textsuperscript{20} This comes to a payload percentage of 0.83%. Our calculation is not as close here, but is still within a factor of two.

Additional missions to achieve GEO and geosynchronous transfer orbit (GTO) can also be computed. Payload percentages to reach SSO and semi-synchronous transfer orbit (STO) are also listed. The $\Delta V$ requirements are based on a Hohmann transfer orbit (see Section 6.4.2, p. 139) from a 200 km LEO orbit to either SSO or GEO.

Again, we can check our results with those of the real world. Our calculation of payload percentage for a liquid single stage from LEO to GEO is 31.9%. The Atlas Centaur-G orbital transfer vehicle has a payload percentage of 23.8%.\textsuperscript{21} Our calculation of a solid two stage vehicle from LEO to GEO is 17%. The Inertial Upper Stage (IUS) two stage solid vehicle has an payload percentage of 13.5%.\textsuperscript{22} The results are roughly correct. I do not have any data to check the SSO calculations.

Also listed in Table 6.2 is the variable effect of the Earth’s rotation. If the satellite is launched from the Equator due East, a potential gain of 0.46 km/sec. If the satellite is launched due West from the Equator (to increase intercept velocity when attacking from a Hohmann orbit), the additional $\Delta V$ required would be 0.46 km/sec. Those

\begin{footnotesize}
\begin{itemize}
\item \textsuperscript{17}“Specifications, International Launch Vehicles,” \textit{Aviation Week & Space Technology}, March 18th, 1991, p. 132.
\item \textsuperscript{19}“Specifications, U.S. Launch Vehicles,” \textit{Aviation Week & Space Technology}, March 18th, 1991, p. 131.
\end{itemize}
\end{footnotesize}
number represent the complete range of costs or benefits of launch from various latitudes into various orbital inclinations. The best case is launching on the Equator at 0 degrees inclination. The worst case is launching in the Equator at 180 degrees inclination.

The costs of launching against the rotation of the Earth (anti-spinward) are expressed as normal payload percentages. Launching with the rotation of the Earth (spinward) provides a reduction in rocket mass. Thus, these payload percentages are expressed as fraction greater than one. To be perfectly correct, one should go through and re-calculate the payload percentages for each possible mission. But these represent approximate factors which can simply by multiplied in to the payload percentages of the mission.

6.4 Re-Evaluation of the Pop-Up Attack

I now return to the problem of comparing the target satellite in orbit with a pop-up attack from the Earth's surface. Our comparison at the end of the last section was based on ΔV and assumed no gravity losses. I can now introduce gravity losses and compare the rocket weights needed to perform each mission.

6.4.1 Target vs Attacker Cost

I calculated in the Section 6.3 that to reach a 200 km height, the liquid rocket would have a payload percentage of 36.2% (19,9% for a solid rocket). This is the only cost the attacker would have to pay. The target, however, must pay this cost as well as the horizontal acceleration cost: 11.36% for a liquid rocket, 2.89% for a solid one.

Thus for the same mass, the target must use a liquid rocket \( \frac{1}{0.1136} = 8.79 \) times as large or a solid rocket rocket \( \frac{1}{0.0289} = 34.6 \) times as large. We can perform a similar calculation at each orbital altitude. The results are shown in Table 6.3. Also included is a comparison giving the target a liquid rocket, while forcing the attacker to use a solid one. Note that under these circumstances, the target derives an advantage at higher orbital altitudes.
<table>
<thead>
<tr>
<th>Orbital Altitude</th>
<th>Attacker Payload %</th>
<th>Target Payload %</th>
<th>Attacker Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Liquid</td>
<td>Solid</td>
<td>Liquid</td>
</tr>
<tr>
<td>200 km, LEO</td>
<td>36.2%</td>
<td>19.9%</td>
<td>4.12%</td>
</tr>
<tr>
<td>1500 km, ULEO</td>
<td>24.0</td>
<td>10.3</td>
<td>3.33</td>
</tr>
<tr>
<td>26,610 km, SSO</td>
<td>2.43</td>
<td>0.227</td>
<td>1.56</td>
</tr>
<tr>
<td>42,421 km, GEO</td>
<td>1.85</td>
<td>0.164</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Table 6.3: Rocket Size Advantages for Pop-Up Attacker vs Target Satellite

Note: The last column assumes the attacker uses solid booster and the target uses a liquid one. Baseline for all cases is the surface of the Earth with zero velocity.

This combined with the earlier finding (see Principle of Satellite Vulnerability) that the attacker need only use $1/1215$th as much mass (in LEO) yields an attacker rocket mass advantage of $1215 \times 8.79 = 10,692$ to $34.6 \times 1215 = 42,039$. However, few satellites are massive enough to allow an ASAT to realize all these advantages.

### 6.4.2 Target Maneuver

I now turn to the question of evasion. I have already established that the launch site must be in or close to the plane of orbit of the target to perform a pop-up attack. But what if the target (having perfect information) maneuvers just as the attacker is launched?

**Attacker Ascent Time**

First I need to know the time of ascent. Taking the 3 stage liquid rocket as the example, I know the burn time ($\tau_b$) is 235 seconds. But I also need to know the time between burn out and moment when the rocket reaches height of 200 km. From the section 6.2.2 Gravity Losses on page 174, I know the velocity at burn out will be:

$$\Delta V = v_e \times \ln(R_m) - g \times \tau_b$$

$v_e$ is 4.606 km/sec and $R_m$ is 2.22, $\Delta V$ is 1.367 km/sec. From this point on, the rocket loses velocity at roughly $9.8 - \frac{m}{sec^2}$ until it reaches zero velocity at height 200 km. Using $Velocity = Acceleration \times Time$, I can deduce that this will take 139 seconds.
<table>
<thead>
<tr>
<th>Ascent Altitude</th>
<th>Time in Seconds</th>
<th>Minutes</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO, 200 km</td>
<td>374</td>
<td>6.24</td>
<td>0.104</td>
</tr>
<tr>
<td>ULEO, 1500 km</td>
<td>830</td>
<td>13.8</td>
<td>0.231</td>
</tr>
<tr>
<td>SSO, 20,232 km</td>
<td>7,585</td>
<td>126</td>
<td>2.11</td>
</tr>
<tr>
<td>GEO, 35,863 km</td>
<td>15,229</td>
<td>254</td>
<td>4.23</td>
</tr>
</tbody>
</table>

Table 6.4: Ascent Times from the Surface of the Earth

Thus, total ascent time is $235 + 139 = 374$ or 6.24 minutes.

We can approximate the time to reach other altitudes by assuming any further stages are burned during this initial coasting period. We also assume the rocket has the necessary velocity as it reaches 200 km, 374 seconds from launch. We then deduce the coasting time to reach target altitude. To reach ULEO, 4.47 km/sec (see Table 4.1, p. 151) is required; to reach SSO, 9.55 km/sec is required; and to reach GEO 10.1 km/sec is required.

We can deduce the ascent time for LEO to ULEO as we did with LEO, dividing 4.47 km/sec by 9.8 m/sq-sec to get 456. Adding this to 374 sec gives us 830 sec. SSO, and GEO are more difficult because we cannot assume the force of gravity holds constant throughout the ascent. The simplest way of dealing with this problem is to use an iterative computer program to determine the time of ascent. The C code used is listed in Appendix D. The results are shown in Table 6.4.

**Engagement**

Six minutes is a short time in which to maneuver. The target moves only $\frac{1}{16}$ of its orbit in that time. Because the distances involved are so small relative to the scale of the Earth's gravitational field, I can model the engagement as one taking place in a uniform vertical gravitational field. That is, I can think of the target as moving in a straight line, rather than an ellipse, and I can assume that the force of gravity is uniform everywhere.

Under these circumstances, the engagement becomes a simple matter of which satellite can produce more $\Delta V$ in the six minutes available. But the target suffers from a great dis-advantage: it maneuver capability must be moving at 7.793 km/sec. That is, the rocket and fuel to provide that maneuver capability must themselves be
launched with the target satellite, requiring a larger rocket. The attackers maneuver capability starts on the Earth’s surface. Thus, the same factor of 8.8 to 34.6 in favor of the attacker applies to any final maneuvers made by either satellite.

Additionally, the mass being accelerated for the attacker is smaller due to the Principle of Satellite Vulnerability. The ASAT needs to be only 1/1215th the mass of the satellite to destroy it (see Chapter 5). Thus the full attacker advantage in rocket mass of 10,692 to 42,039 (see Section 6.4.1, p. 181) applies to the end-game as well. The problem with these numbers is that the smallest ASAT is 4.5 kg. There are no satellite in orbit that are 45,000 kg. So an ASAT is unlikely to be able to realize all these numerical advantages.

6.4.3 Targets in GEO

LEO, of course provides all of the advantages to the attacker. At GEO altitudes, the payload percentages are almost the same. The closing velocity drops to 3.067 km/sec. At this closing velocity, the attacker mass advantage shrinks to a factor of 188.

Even this attacker advantage is in doubt. Attempting to ascend straight upward to GEO would involve large gravity losses. Instead, the attacker is forced to use a geosynchronous transfer orbit (GTO). This is, in effect, a co-orbital attack. Even if the attacker were willing to pay the costs of direct ascent, the time and scale involved would make the final engagement the same as a co-orbital attack. The attacker has time to maneuver, and the force of gravity changes appreciably over the height of the ascent.

Also, the attacker has expended almost as much ΔV in reaching GEO altitude as the attacker did in entering GEO orbit. Thus, the maneuver costs for both sides are almost equal.

In short, almost every attacker advantage vanishes at GEO altitude. The only advantage that still applies is the mass needed to kill the target. However, the dis-advantages of co-orbital attack come in to play and may, in fact, put the attacker at a dis-advantage.
6.4.4 Summary

In LEO the target needs a rocket 8.8 times the size of the attacker if their rockets are liquid fueled, and 34.6 times if they are solid fueled, for the same payload. But as we know from Chapter 5, the required payload for a KKV ASAT is much smaller than the satellite it kills, so these factors multiply. At GEO, most attacker advantages are eliminated.

Of course, many other factors will determine the outcome. In the next section we will learn that launch costs are not linear: larger payloads are cheaper per kg than small ones. The target must be seen, the attacker must be in the right position at the right time. The defender can employ decoys and self-defense measures. These factors are discussed in Chapter 9. But an examination of these points would not have been necessary had we not first established that the target satellite in Earth orbit is profoundly vulnerable to conventional attack. Three to four orders of magnitude is a big advantage to start with.

I now return to the World War II example of the torpedo bomber vs the battleship. The bomber weighing only a few tons could sink a battleship weighing 58,000 tons,\textsuperscript{23} an attacker advantage of 4 orders of magnitude. This fact profoundly altered naval warfare in the mid 20th century. This ground-based conventional ASAT represents a space equivalent of the torpedo bomber.

6.5 Rocket Inventory: Launch Costs

In this section I construct a model for computing launch costs based on payload weight and mission. I begin by determining the cost to launch various sized payloads into LEO by surveying existing launch vehicles. Next, using the LEO data as a base line, I use the rocket model developed earlier in this Chapter to predict the launch costs to reach GTO and GEO. We can then compare the predicted cost to the actual cost based on a survey of GTO and GEO launch vehicles. As we will see, the model

and the survey are always within a factor of two of each other, and are often much closer.

This gives us a model for determining the approximate cost to put any payload into any orbit. I begin with the survey of launcher costs and payloads. The results of this survey are shown in Table 6.5.

### 6.5.1 Rocket Survey


The Titan IV with a Centaur G upper stage costs $264 million according to one source\(^24\) and $180 million in another.\(^26\) I’ve used an average of $222 million. Launch weight is 868,386 kg and it will put 12,000 kg to GTO and 4,600 kg to GEO. The Centaur upper stage used with the Titan weighs 17,575 kg, not including payload.

The Titan IV with an IUS upper stage, weighs 857,057 kg. Payload to GEO is 2,409 kg. The IUS weighs 12,187 kg, not including payload.

The Titan IV with no upper stage (NUS) will lift 17,450 kg into LEO or 8500 kg into GTO, at a cost of $150 million. The launch weight is not available, but we can compute it. If we take away the payload and upper stages weights from the other two Titan IV weights we get 846,211 kg and 842,461 kg, 844,000 kg seems a pretty good

\(^{24}\)Wong in Wertz, p. 671

guess as to weight for the Titan IV without payload or upper stage. Adding in the LEO payload, the launch weight total is 861,450 kg.

The Titan 34D with a Transtage weighs 688,545 kg. Payloads are 4,626 to GTO,26 and 1,909 kg to GEO. Without a Transtage, payload to LEO is 13,636 kg.27 Cost for either system is roughly $110 million.28 With a Centaur upper stage, payloads are 17,727 kg to LEO and 4,545 kg to GEO.29

The Commercial Titan has a launch weight of 593,636 kg, costs $125 million per launch, and can put 14,545 kg into LEO and 5,000 kg into GTO.30

The Titan III with an IUS has a similar performance with that of the Commercial Titan. The rocket mass and cost are not known.

The Delta 3920 with a PAM-D upper stage has a launch weight of 192,300 kg, costs $50 million per launch, and puts 730 kg into GEO.31

The Delta 6925 (a Delta 6920 with a PAM-D upper stage) has a launch weight of 219,863 kg and costs $55 million per launch. Payloads are 3,909 kg to LEO, 1,420 kg to GTO, and roughly 635 kg to GEO. The payload to GEO figure requires an apogee kick motor; I don’t know its mass.

The Delta 7925 (a Delta 7920 with a PAM-D upper stage) has a launch weight of 232,273 kg. Payloads are 4,855 kg to LEO and 1,820 kg to GTO. The reliability of the Delta rockets over the last nine years has been 97.8% .32

The Atlas G Centaur (the name does not mean it has a Centaur G upper stage) launch weight is 163,909 kg. Cost is $72 million per launch. Payloads are 2,364 kg to GTO and 1,330 kg to GEO. Reliability for the Atlas is 95% .33

The Scout 2 launcher will cost $15.5 million each and will launch 600 kg into a

---

29 Aviation Week & Space Technology September 11th, 1989, p. 41.
32 Source number 13, p. 101.
278 km orbit with 95% reliability.\textsuperscript{34} The Scout weighs 31,300 kg.\textsuperscript{35}

The Chinese Long March 3 booster can put 3000 kg into LEO and 1300 kg into GTO. Launch weight is 203,000 kg.\textsuperscript{36} Launch cost is only $30 million, but this is thought to be a low price to get market share. Because of its uncharacteristically low cost, we will not include this rocket in our LEO cost calculations.

The Chinese CZ-2E has a launch weight of 464,841 kg. Payloads are 8,800 kg to LEO or 4,500 kg into GTO.\textsuperscript{37}

The Chinese CZ-3A has not yet flown, but is expected to put 8,500 kg into LEO\textsuperscript{38} and 2500 kg into GTO. Launch weight is to be 240,437 kg.

International Mircospace Inc. is offering 182 kg to LEO aboard its Orbital Express for $4.5 million.\textsuperscript{39}

The Ariane 3 weighs 237,000 kg and will lift 2,580 kg into GTO.\textsuperscript{40}

The French Arianespace Ariane 4 will launch 17,800 kg into LEO for $115 million. Auxiliary payload aboard an Ariane rocket of up to six satellites of up to 50 kg each will be launched in to LEO for $ 600,000.\textsuperscript{41}

The Ariane 44L, a stretched version of the Ariane 4, weighs 470,000 kg and can put 7,000 kg into LEO and 4,200 kg into GTO.\textsuperscript{42} The

Ariane 5, which has not yet flown, will weigh 725,000 kg and can put 6,900 kg into GTO.\textsuperscript{43} I estimate the cost at $75 million.\textsuperscript{44}

\textsuperscript{34}Aviation Week & Space Technology April 10th, 1989, p. 25.
\textsuperscript{36}Aviation Week & Space Technology April 16th, 1990, p. 25.
\textsuperscript{37}Aviation Week & Space Technology July 23rd, 1990, p. 31.
\textsuperscript{41}Aviation Week & Space Technology March 19th, 1990, p. 192.
\textsuperscript{44}Ariane 5 is supposed to cost only 55% per kg of the cost for the Ariane 44L (see Interavia Space Directory 1989-1990, p. 320). The cost per kg to GTO for the 44L is $84m / 4,200 kg = 20,000 $/kg. 55% of that is 11,000 $/kg. Given an Ariane 5 payload to GTO of 6,800 kg, this comes to a total cost of $74.8 million or roughly $75 million.
Figure 6-1: Launch Cost Rates into LEO as a Function of Payload
Note: circles indicate boosters which have not yet flown. Ariane Auxiliary payloads and Long March 3 points are not included in linear estimate as they do not reflect real costs. Linear estimate based on least squares estimation using linear x axis scale.

The Pegasus launcher will put 455 kg into LEO for $8 million. Launch weight from a B-52 at 42,000 ft., is 18,636 kg.

The Space Shuttle with and IUS upper stage will put 2,270 kg into GEO for $270 million. This is what NASA charges for satellite missions, but actual Shuttle costs are unknown. Shuttle costs are high compared to other systems. We will therefore not include Shuttle costs in our GEO cost calculations.

It is estimated that a rebuilt Saturn V could put 280,000 into LEO for $600 million.

The Japanese H-2 has a launch weight of 240,000 kg and will put 9020 kg into LEO, 3820 into GTO, and 2000 kg into GEO. The cost is estimated at $117 million.\(^{45}\)

---

<table>
<thead>
<tr>
<th>Booster</th>
<th>Upper Stage</th>
<th>Launch Weight in Kg</th>
<th>LEO Payload in Kg</th>
<th>GTO Payload in Kg</th>
<th>GEO Payload in Kg</th>
<th>Cost in Millions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titan IV</td>
<td>None</td>
<td>861,450</td>
<td>17,450</td>
<td>8,500</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Titan IV</td>
<td>Centaur G</td>
<td>868,386</td>
<td>-</td>
<td>12,000</td>
<td>4,600</td>
<td>≈222</td>
</tr>
<tr>
<td>Titan IV</td>
<td>IUS</td>
<td>857,057</td>
<td>-</td>
<td>-</td>
<td>2,409</td>
<td>-</td>
</tr>
<tr>
<td>Titan 34D</td>
<td>None</td>
<td>-</td>
<td>13,636</td>
<td>-</td>
<td>-</td>
<td>≈110</td>
</tr>
<tr>
<td>Titan 34D</td>
<td>Transtage</td>
<td>688,545</td>
<td>-</td>
<td>4,626</td>
<td>1,909</td>
<td>≈110</td>
</tr>
<tr>
<td>Titan 34D</td>
<td>Centaur</td>
<td>17,727</td>
<td>-</td>
<td>4,545</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Commercial Titan</td>
<td>None</td>
<td>593,636</td>
<td>14,545</td>
<td>5,000</td>
<td>-</td>
<td>125</td>
</tr>
<tr>
<td>Titan III</td>
<td>IUS</td>
<td>-</td>
<td>14,400</td>
<td>5,000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Delta 3920</td>
<td>PAM-D</td>
<td>192,300</td>
<td>-</td>
<td>-</td>
<td>730</td>
<td>50</td>
</tr>
<tr>
<td>Delta 6925</td>
<td>PAM-D</td>
<td>219,863</td>
<td>3,909</td>
<td>1,420</td>
<td>≈635</td>
<td>55</td>
</tr>
<tr>
<td>Delta 7925</td>
<td>PAM-D</td>
<td>232,273</td>
<td>4,855</td>
<td>1,820</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Atlas G Centaur</td>
<td>None</td>
<td>163,909</td>
<td>-</td>
<td>2,364</td>
<td>1,330</td>
<td>72</td>
</tr>
<tr>
<td>Scout 2</td>
<td>None</td>
<td>31,300</td>
<td>≈600</td>
<td>-</td>
<td>-</td>
<td>15.5</td>
</tr>
<tr>
<td>Long March 3</td>
<td>None</td>
<td>203,000</td>
<td>3,000</td>
<td>1,300</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>CZ-2E</td>
<td>None</td>
<td>464,841</td>
<td>8,800</td>
<td>4,500</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CZ-3A</td>
<td>None</td>
<td>240,437</td>
<td>8,500</td>
<td>2,500</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Orbital Express</td>
<td>None</td>
<td>-</td>
<td>182</td>
<td>-</td>
<td>-</td>
<td>4.5</td>
</tr>
<tr>
<td>Ariane 3</td>
<td>None</td>
<td>237,000</td>
<td>-</td>
<td>2,580</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ariane 4</td>
<td>None</td>
<td>-</td>
<td>17,800</td>
<td>-</td>
<td>-</td>
<td>115</td>
</tr>
<tr>
<td>Ariane 44L</td>
<td>None</td>
<td>470,000</td>
<td>7,000</td>
<td>4,200</td>
<td>-</td>
<td>84</td>
</tr>
<tr>
<td>Ariane 4 Aux</td>
<td>None</td>
<td>-</td>
<td>300</td>
<td>-</td>
<td>-</td>
<td>0.6</td>
</tr>
<tr>
<td>Ariane 5</td>
<td>None</td>
<td>725,000</td>
<td>-</td>
<td>6,900</td>
<td>-</td>
<td>≈75</td>
</tr>
<tr>
<td>Pegasus</td>
<td>None</td>
<td>18,636</td>
<td>455</td>
<td>-</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>Shuttle</td>
<td>IUS</td>
<td>-</td>
<td>-</td>
<td>2,270</td>
<td>-</td>
<td>270</td>
</tr>
<tr>
<td>Saturn V</td>
<td>None</td>
<td>-</td>
<td>280,000</td>
<td>-</td>
<td>-</td>
<td>≈600</td>
</tr>
<tr>
<td>H-2</td>
<td>None</td>
<td>240,000</td>
<td>9,020</td>
<td>3,820</td>
<td>2,000</td>
<td>≈117</td>
</tr>
</tbody>
</table>

Table 6.5: Booster Costs and Performance

Notes: Launch weight includes payload and upper stage weight. Long March 3 price is considered below cost. Scout 2, CZ-3A H-2, and Orbital Express have not flown. LEO is defined as a circular orbit at 200 km altitude. Exception: Scout 2 LEO orbit is 278 km altitude. Pegasus launcher is launched from a flying B-52 at 42,000 ft.
Figure 6.2: Launch Cost Rates into GTO as a Function of Payload
Note: linear estimate based on equivalent LEO launch costs and model rocket based on average of liquid and solid payload percentages (41.6%).
Figure 6-3: Launch Cost Rates into GEO as a Function of Payload
Note: linear estimate based on equivalent LEO launch costs and model rocket based on average of liquid and solid payload percentages (25%).
<table>
<thead>
<tr>
<th>Booster</th>
<th>Upper Stage</th>
<th>Surface to LEO</th>
<th>Surface to GTO</th>
<th>LEO to GEO</th>
<th>LEO to GTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Booster Payload Percentages:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titan IV</td>
<td>None</td>
<td>2.0</td>
<td>0.99</td>
<td>49</td>
<td>–</td>
</tr>
<tr>
<td>Titan IV</td>
<td>Centaur G</td>
<td>–</td>
<td>1.4</td>
<td>0.53</td>
<td>38</td>
</tr>
<tr>
<td>Titan IV</td>
<td>IUS</td>
<td>–</td>
<td>–</td>
<td>0.28</td>
<td>–</td>
</tr>
<tr>
<td>Titan 34D</td>
<td>Transtage</td>
<td>–</td>
<td>0.67</td>
<td>0.28</td>
<td>41</td>
</tr>
<tr>
<td>Titan 34D</td>
<td>Centaur</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>26</td>
</tr>
<tr>
<td>Commercial Titan</td>
<td>None</td>
<td>2.4</td>
<td>0.84</td>
<td>34</td>
<td>–</td>
</tr>
<tr>
<td>Titan III</td>
<td>IUS</td>
<td>–</td>
<td>–</td>
<td>35</td>
<td>–</td>
</tr>
<tr>
<td>Delta 3920</td>
<td>PAM-D</td>
<td>–</td>
<td>–</td>
<td>0.38</td>
<td>–</td>
</tr>
<tr>
<td>Delta 6925</td>
<td>PAM-D</td>
<td>1.8</td>
<td>0.65</td>
<td>0.29</td>
<td>36</td>
</tr>
<tr>
<td>Delta 7925</td>
<td>PAM-D</td>
<td>2.1</td>
<td>0.78</td>
<td>–</td>
<td>37</td>
</tr>
<tr>
<td>Atlas G Centaur</td>
<td>None</td>
<td>–</td>
<td>1.4</td>
<td>0.81</td>
<td>–</td>
</tr>
<tr>
<td>Scout 2</td>
<td>None</td>
<td>1.9</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Long March 3</td>
<td>None</td>
<td>1.5</td>
<td>0.64</td>
<td>–</td>
<td>43</td>
</tr>
<tr>
<td>CZ-2E</td>
<td>None</td>
<td>1.9</td>
<td>0.97</td>
<td>–</td>
<td>51</td>
</tr>
<tr>
<td>CZ-3A</td>
<td>None</td>
<td>3.5</td>
<td>1.0</td>
<td>–</td>
<td>29</td>
</tr>
<tr>
<td>Ariane 3</td>
<td>None</td>
<td>–</td>
<td>1.1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Ariane 44L</td>
<td>None</td>
<td>1.5</td>
<td>0.89</td>
<td>–</td>
<td>60</td>
</tr>
<tr>
<td>Ariane 5</td>
<td>None</td>
<td>–</td>
<td>0.94</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Pegasus</td>
<td>None</td>
<td>2.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>H-2</td>
<td>None</td>
<td>3.8</td>
<td>1.6</td>
<td>0.83</td>
<td>42</td>
</tr>
</tbody>
</table>

Model Payload Percentages from Table 6.2, p. 179:

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Rockets</td>
<td>4.1</td>
<td>2.1</td>
<td>1.4</td>
<td>50</td>
<td>33</td>
</tr>
<tr>
<td>Solid Rockets</td>
<td>0.58</td>
<td>0.19</td>
<td>0.099</td>
<td>33</td>
<td>17</td>
</tr>
</tbody>
</table>

Average Payload Percentages:

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Booster</td>
<td>2.3</td>
<td>0.99</td>
<td>0.49</td>
<td>42</td>
<td>29</td>
</tr>
<tr>
<td>Average Solid/Liquid Model</td>
<td>2.3</td>
<td>1.1</td>
<td>0.75</td>
<td>42</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 6.6: Booster Payload Percentages
is, the cost of bringing up the rocket mass to LEO is much larger than the cost of the rocket itself. Thus, we can think of the cost of putting an object into GTO to be the same as putting two and a half times its mass into LEO. This is its LEO equivalent mass. This is not the same as multiplying the cost by two and a half. As Figure 6-1 demonstrates, the larger the payload, the less its cost per kg. Because the LEO equivalent mass is larger, it costs less per kg. Thus, the GTO launch cost for a given payload is less than two and a half times the LEO launch cost for the same payload.

Applying the average payload percentage of 41.6%, we apply it to Equation 6.4 to get a cost estimate for reaching GTO:

\[
\frac{1}{0.416} \left[ 26,400 - 7,750 \times \log_{10} \left( \frac{\text{Payload (kg)}}{100 \times 0.416} \right) \right] =
\]

\[
\frac{1}{0.416} \left[ 26,400 - 7,750 \times \log_{10} \left( \frac{1}{0.416} \right) - 7,750 \times \log_{10} \left( \frac{\text{Payload (kg)}}{100} \right) \right] =
\]

\[
GTO \text{ Launch Cost (}$/\text{kg}$) = 56,400 - 18,600 \times \log_{10} \left( \frac{\text{Payload (kg)}}{100} \right)
\]

This estimate is plotted in Figure 6-2, along with the available data we have from the survey. For reference, the LEO cost estimate is also plotted. As the reader can see, the data and the estimate are fairly close, and always within a factor of two. I take this to be an indication that the cost model is a reasonable one.

### 6.5.4 GEO Cost Estimate

I repeated this computation process for reaching GEO from LEO. The rocket model estimated payload percentage to GEO from LEO is 33.5% for liquid boosters and 17.1% for solid ones. This comes to an average of 25.3%. Applying this percentage to the LEO base line estimate gives us a GEO cost estimate of:
\[ \text{GEO Launch Cost (\$/kg)} = 86,100 - 30,600 \times \log_{10} \left( \frac{\text{Payload (kg)}}{100} \right) \]

The result and available data are plotted in Figure 6.3. Also plotted for reference are the LEO and GTO cost estimates. The data and the estimate are not as close this time. The best that can be said for the estimate is that it represents a minimum cost, and that is still within a factor of two of the data. There are a number of possible reasons for the lack of fit. In the rocket model developed in Chapter 6, we used specific impulses at the high range of possible performance. Thus, the rockets in the model are likely to perform better (and therefore cost less) than those in reality.

Nonetheless, I feel that the GEO cost estimate, although low reflects the correct slope of the data presented. Further, both the GTO and GEO cost estimates seem to have captured the changing slopes of higher orbit payloads as reflected by the plotted data. Overall, I feel that the model derived here based on the LEO launch cost baseline is a reasonable one to use for estimating the cost of payload delivery in the future.

6.5.5 Summary

We now have a model for determining the cost of any mission given the payload. The model is rather crude, accurate to within a factor of two, but that will be sufficient for our purposes. As we begin to compare the costs of destroying satellites with the costs of launching them, we will see that the differences are much larger than a factor of two.
Chapter 7

Laser ASATs

In this chapter we examine the feasibility of laser ASATs. We begin with an analysis of space-based lasers, and then move on to ground-based lasers. Finally, we determine the necessary improvements, if any, that are required to destroy satellites under a variety of assumptions.

7.1 Space-Based Lasers

Space-based lasers may be very effective in destroying satellites, but they can only perform this mission if they are able to defend themselves from kinetic attack. If space-based lasers are vulnerable to kinetic ASATs, then they have no potential as an ASAT system. The question is: are ablative shields tough enough to shield a kinetic ASAT long enough to kill a space-based laser?

Modern ablative materials can absorb 60,000 Joules per gram while evaporating.\(^1\) A Watt is one Joule per second. Current designs for space-based lasers are expected to be scalable up to 10 Mega Watts (at wavelength of $\lambda = 2.7 \ \mu m$).\(^2\) A typical

\(^1\) Velikhov, Yevgeni, Roald Sagdeev, and Andrei Kokoshin, editors. *Weaponry in Space: The Dilemma of Security*, Mir Publishers, Moscow, 1986., Table 1.2, p. 22. This estimate is confirmed in the APS Study, p. S125 which states that ablative materials can absorb 32 kJ/gm and that by embedding Tungsten in the shielding the reflectivity can be increased to 0.50. Result: 64 KJ/gm absorption capacity.

space-based laser of the future is expected to put out about 25 Mega Watts (MW) of power.³

7.1.1 Laser in LEO

How vulnerable is a laser in LEO to kinetic ASAT attack? I make two simplifying assumptions: first, that all of the laser’s power can be focused into the attacking ASAT from the moment of its launch; and second, that the energy is evenly deposited onto the kinetic ASAT’s heat shield. This ignores the problems of pointing and tracking. These assumptions also ignore the atmospheric distortions and absorptions while the ASAT is still inside the Earth’s atmosphere. I also assume that it takes 6.24 minutes (375 sec) for the ASAT to intercept (see Section 6.4.2, page 182).

The total energy the ASAT ablative shield would be required to absorb would be:

\[
25 \text{ Mega Watts} \times 375 \text{ seconds} = 9.375 \times 10^9 \text{ Joules}
\]

And the mass of the shield required to absorb that amount of energy would be:

\[
\frac{9.375 \times 10^9 \text{ Joules}}{60,000 \text{ Joules/gm}} = 156,250 \text{ gm} = 156 \text{ kg}
\]

This is a large mass compared to the weight of the the ASAT, but a LEO-based laser is expected to weigh tens of thousands of kilograms. Thus the attacker has an enormous advantage over the defender. Thus, LEO-based laser ASAT’s, while perhaps effective against other satellites, are themselves too vulnerable to be effective.

7.1.2 Laser in GEO

What about a KKV attack against a laser in GEO? Another way of thinking of the absorption capacity of the shield is in Kilograms vaporized per second by a 25 Mega Watt beam. This comes to

\[
\frac{25 \times 10^6 \text{ Joules/sec}}{60,000 \text{ Joules/gm}} = 416 \text{ gm/sec} = 0.416 \text{ kg/sec}.
\]

Let’s assume pop-up attack for the ASAT. The ascent times are listed in Table 6.4 (p. 183). Ascending to GEO would require 15,229 sec (4.23 hours). Against a 25 MW laser, this would require 6,225 kg. This is a lot of weight to put into GEO, but still far less than the laser. The question is exactly how much less?

**Relative Mass Consumption**

Another way to approach the problem is by looking at fuel consumption. The current chemical space-based laser under development is expected to consume 100 lb./sec or 45.5 kg/sec of fuel to generate 10 MW of power.\(^4\) Thus, 25 MW would consume:

\[
\frac{25 \text{ MWatts}}{10 \text{ MW}} \times 45.5 \text{ kg} = 113.7 \text{ kg/sec}
\]

While the Laser is burning 113.7 kg/sec to illuminate the approaching ASAT, the ASAT is losing 0.416 kg/sec in ablative shielding. In other words the attacker has an inherent weight advantage of more than a factor of 270 over the space-based laser, wherever it is orbiting. This leads to the following principle:

**Principle of Space-Based Lasers vs Kinetic Kill ASATs:** Space-based lasers consume chemical fuel roughly 270 times faster (by weight) than ablative shielding is vaporized off of the attacking ASAT. Therefore, space based lasers are vulnerable to kinetic kill ASATs.

### 7.1.3 Complicating Factors

Of course, in order to create a laser-killing kinetic ASAT, some additional engineering would be required. The ASAT would probably have to spin in order to distribute the

laser beam evenly over the entire shield. The F-15 based MHV ASAT, for example, spins as it approaches its target.

Sensing equipment would have to be constructed to work under laser illumination. This might seem difficult given the sensitivity of the IR telescopes that are part of current ASAT's. But recall that these sensors are designed to pick out satellites from the blackness of space. If the target is illuminating the ASAT, sensitive equipment is no longer required. The target satellite is revealing its location in a very obvious way. Under these circumstances, heavily shielded—but not very sensitive—sensors would be required once the target laser attacked.

These engineering and shielding requirements would certainly add to the weight of the attacking ASAT. But consider that the above conclusion assumes that the entire shield is carried to the target. In fact, most of the shield has melted off by the time the attacking ASAT reaches the target. Thus the actual delivered weight of the shield is much less that its initial weight. I am crediting the weight savings of the melted shield toward the necessary engineering additions above, and calling it even. I think the kinetic attacker weight advantage of a factor of 270 is quite conservative.

Recall that this mass savings is in addition to the attacker advantages listed in previous chapters. Not only do orbital mechanics and hypervelocity impact give the attacker a mass advantage, but that advantage is multiplied by 270 when considering the case of attacking a laser. That is, the fuel used by the laser under attack must be placed into orbit, while the mass of the attacker's shield need only reach the orbit of the target laser.

The obvious conclusion is that space-based laser ASATs simply aren't worth the trouble. They depend on technology that is still far off, and they can be defeated by technology available today: the kinetic ASAT.

We now turn to a discussion of ground-based laser ASATs.
7.2 Ground-Based Lasers

It is theoretically possible to use ground-based lasers to destroy satellites. If practical, such a capability would present obvious advantages over a hit-to-kill system. With the exception of satellites in GEO, all satellites eventually pass over any given location on the Earth, provided the satellites orbital inclination is greater than the location’s latitude. Satellites in GEO have a zero inclination, but because they are so high, they are visible to all site within 81 spherical degrees. In the case of satellites in LEO, satellites would pass near any ground-based laser location (within 11 degrees longitude) twice a day. Since the ground-based laser could be a multi-shot weapon, one can imagine a single site clearing the skies of enemy satellites in 12 hours.

The reality is much different. Current technology is very far from achieving this dream. Many technologies must be improved by orders of magnitude to threaten satellites at LEO, let alone those in GEO. Some of these physical problems may remain unsolvable for decades. Additionally, there are simple countermeasures that can be adopted to shield satellites. With enough money and enough technology and enough power and enough luck, a practical ground-based laser ASAT may become a reality—but it is uncertain.

I now turn to a more detailed discussion of the technical requirements of a ground-based laser ASAT. I begin with a discussion of mirrors, then propagation of the laser beam through the atmosphere, and finally shielding.

7.2.1 Mirrors

A powerful laser will require large optics. The theoretical maximum performance of optics based on the quantum mechanical limitations of photons is called the diffraction limit. The diffraction pattern created is a spot within concentric rings. These rings are of lower intensity than the spot, so we can ignore them and concentrate on the high intensity spot. The spot contains 84% of the beam energy.\footnote{Roy, A. E., and C. Clarke \textit{Astronomy: Principles and Practice} Adam Hilger Ltd., Bristol, p. 216.} Its diameter, measured
in radians, is equal to 1.22 times the wavelength ($\lambda$) divided by the diameter of the focusing mirror ($D$). The cross-sectional area of the beam increases as the square of the distance to the target ($L$). Thus the area of the laser beam (provided $L, \lambda$, and $D$ are all in the same units of measure) is:\(^6\)

$$\text{Area} \cong \left( \frac{1.22 \lambda L}{D} \right)^2 \quad (7.1)$$

For example, if $L = 200$ km, the mirror is 1.22 m across, and the wavelength is 1 $\mu$m, the beam area is 0.04 square meters, or 400 square centimeters. A larger mirror means a smaller beam area. A smaller beam area means more power per unit area and more damage done to the target.

So the attacker wants as large a mirror as possible. How big a mirror is possible? The Hubble Space Telescope’s mirror is 2.4 m across. Using segmented mirrors (several mirrors fit together), 4 m telescope mirrors have been built. This technology is apparently limited to 10 m.\(^7\) For the purposes of this dissertation I will assume current technology can make a mirror 4 m in diameter, and that in the future, a mirror of 10 m might be possible.

It is always conceivable that some new technology will produce even larger mirrors. I feel, however, that these assumptions are generous considering what the mirror must do that a telescope mirror does not. This mirror will have to be manufactured with a highly precise surface (something that the Space Telescope demonstrated is difficult to do). It will have to maintain this precision while reflecting a very powerful laser beam. Thus, thermal expansion will have to be monitored and controlled. The mirror will have to be able to slew quickly (a max of $\tan^{-1}\left(\frac{8 \text{km/} \sec}{200 \text{km}}\right) = 2.3$ Degrees/sec to track LEO targets). Finally, as we shall see below, this mirror will also have to be flexible and under computer control to compensate for turbulence in the atmosphere. It seems to me quite a generous assumption that a mirror at the limit of current technology will be able to do all these things as well. I believe that 10 m is a liberal

\(^6\)APS Study, p. S102.

\(^7\)APS Study, p. S90 and “Eyes on the stars, feet on the ground” The Economist, October 17th, 1992, pp. 96-98.
assumption for mirror diameter.

7.2.2 Atmospheric Absorption and Laser Frequency

The largest problem a ground-based laser ASAT has to face is firing through the atmosphere. The atmosphere absorbs laser light at various frequencies. The shortest wavelength (highest frequency) that the atmosphere will transmit is about 0.36 to 0.50 $\mu m$.\(^8\) Remember that shorter wavelengths require smaller optics, so shorter is better. Above the 0.50 $\mu m$ wavelength, components of the atmosphere absorb most of the laser energy at certain wavelengths, causing "gaps." The highest powered lasers to date (2 Mega Watts) are in the 2.7 $\mu m$ range. But this is a wavelength "gap," where the atmosphere absorbs most of the laser's energy.\(^9\) I will assume that ground-based lasers will operate in the 1 $\mu m$ region. This is better than the best current laser by a factor of two, and worse than the theoretical limit by a factor of two. Also, one is an easy number to work with.

7.2.3 Atmospheric Turbulence

If absorption were the only effect the atmosphere had on lasers, they might be a viable weapon, but other effects complicate the problem further. The atmosphere is an active, turbulent medium. Even on the calmest days, the atmosphere contains eddies which create areas of varying density with varying indices of refraction.\(^10\) These vortices act as lenses, distorting and bending the light which passes through them. Turbulence is what makes the stars appear to twinkle at night when viewed from the surface of the Earth.

Atmospheric turbulence effects on laser intensity is dramatic. The diffraction limit equation (7.1) above can be modified to account for the distorting effects of the turbulent atmosphere by adding a multiplier. The beam area now becomes:\(^11\)

---

\(^8\)APS Study, pp. S100-101, Figure 5.15.
\(^9\)Velikov, p. 28, and APS Study, Figure 3.6, p. S39.
\(^10\)"Eyes on the stars, feet on the ground" The Economist, October 17th, 1992, pp. 96-98.
\[ \text{Area} \approx \left( \frac{1.22\lambda L}{D} \right)^2 \times \left[ 1 + \left( \frac{D}{r_0} \right)^2 \right] \] (7.2)

where \( r_0 \) is the "coherence length" and scales linearly with \( \lambda \). For the visible spectrum \( r_0 \) is 5 to 10 cm. If we take 0.5 \( \mu m \) as the center of the visible spectrum (0.4 to 0.7 \( \mu m \)), we multiply \( r_0 \) by two to account for our theoretical laser wavelength of 1 \( \mu m \). Taking the lower value (5 cm) and multiplying by two, we get an \( r_0 \) of 10 cm for our laser wavelength. Thus if the mirror diameter (\( D \)) is 10 m and \( r_0 \) is 0.10 m, then the laser beam area increases by four orders of magnitude. This means the fluence on the target satellite is diluted by four orders of magnitude as well. Atmospheric turbulence is a significant problem for ground-based lasers.

**Rubber Mirrors**

A potential method of avoiding this \( 10^4 \) turbulence penalty is to use adaptive optics. If the effects of the turbulence along the beam path were known in advance, then a flexible mirror could be used to compensate for them, producing a focused beam as it emerged from the atmosphere. Experiments have been performed to do just this. The experimental device uses a reference "beacon" (a laser at or near the target location) which shines a laser through the atmosphere to a sensor at the ground-based laser. The atmosphere distorts the beacon laser beam. These distortions are then transmitted to the "rubber mirror" which is used to transmit the high power laser to the target. A rubber mirror is a mirror that is deformable; that is, portions of the mirror can be moved by actuators to create controlled distortions. They are not actually made of rubber. The distorted beam then goes through the turbulence exactly reversing the effects on the beacon's beam. The laser then emerges from the atmosphere and at the target as a focused beam. Experiments have been successfully conducted using a deformable mirror 0.5m in diameter.\(^{12}\)

A rubber mirror requires one actuator for every 10x10cm area of the mirror (the value of \( r_0 \) squared).\(^{13}\) The total number of actuators for a mirror of size \( D \) is:

\(^{12}\)APS Study, p. S103.
\(^{13}\)APS Study, p. S103.
\[ \left( \frac{D}{r_0} \right)^2 = \text{Number of Actuators} \]

The current 0.5m mirror requires \( (\frac{0.5}{0.10})^2 = 25 \) actuators. A 10m mirror will require 10,000, an increase of two to three order of magnitude. Presumably, with enough actuators, and a parallel processor to compute their movements, such a mirror could be built.

**Where's the Beacon?**

What is less possible is that a target satellite will be cooperative enough to allow a beacon satellite next to it to allow it to be destroyed. This idea of using a beacon satellite was conceived as part of the Star Wars program to reflect a ground-based laser off space-based mirrors to destroy Soviet ICBM’s during their boost phase. Now, if the laser is firing at a mirror in space, the beacon source must be slightly ahead of the target to account for the time required for the beacon laser light to reach the sensor, for processing time, and for the weapon’s laser light to reach the target. Thus, the “targets” would be cooperating in getting a focused beam to their mirrors by having a beacon satellite just the right distance ahead of them in orbit.

But a hostile satellite is not likely to be so helpful. In fact, it is unlikely that a ground-based laser system that required a beacon satellite to be placed in front of every target satellite would be effective. Why not have the beacon satellite kill the satellite and forego the laser entirely?

It now seems possible to use a ground-based laser to provide the necessary beacon. Astronomers are currently developing a technique of using a ground-based laser to excite Sodium atoms in the upper atmosphere.\(^{14}\) The Sodium is deposited in the atmosphere, at an altitude of 98 km,\(^{15}\) by meteors as they burn up. A laser tuned to the

\(^{14}\)“Livermore Technology May Boost Detail of Earth-Bound Astronomy” *Aviation Week & Space Technology*, January 6th, 1992, p. 57

\(^{15}\)Re-entry burning begins at 98. This is where the atmosphere becomes dense enough to cause significant heating. See Collins, John M. *Military Space Forces, The Next 50 Years*, Pergamon-Brassey’s International Defense Publishers, Washington D.C., 1988, Map 2, p. 9.
right wavelength can excite these atoms to emit photons. The resulting light is sufficient to apply adaptive optics to resolve images from space through the atmosphere at close to the diffraction limit.\textsuperscript{16}

But the point remains that turbulence represents a $10^4$ degradation in laser intensity. Adaptive optics may be able to recover some or all of the losses, but problems still exist. A rubber mirror will require 400 times the current number of actuators, and will be required to operate with precision under intense laser light. Of more importance, the atmosphere simply may not transmit a laser beam at these energy densities.

### 7.2.4 Thermal Blooming

Another atmospheric problem results from firing intense lasers through the atmosphere. Most of the energy passes through (assuming a non-absorbing frequency is used), but some is absorbed. As the atmosphere heats up, its density decreases, changing its index of refraction. The hot air acts as a lens to distort and broaden the beam. This phenomenon is not well understood, although it has been observed. It is possible that computer models of the atmosphere might allow a rubber mirror to compensate for the effect. The computer would use an atmospheric model to anticipate the phenomenon. Complications arise when winds blow the heated air around or the beam is moved, creating eddies of hot and cold air. In short, the heated atmosphere might be too complex to model. Thermal blooming might simply impose a limit on the amount of laser energy that the atmosphere can transmit.

\ldots it is not clear that atmospheric data can be obtained at required rates and employed in adaptive optical system so as to achieve predictive and iterative blooming compensation at significant fluence level in the 10 –

\textsuperscript{16}Conversations with Dr. Myron Lecar and Peter Nisenon, Harvard Astronomical Observatory, Harvard University, Cambridge, August and September, 1991. Precise pointing also appears not to be problem. The Relay Mirror Experiment (RME) spacecraft has flew, "demonstrating a precise control capability at the sub-microradian level, according to defense officials." A laser was moved over a target with feedback to spell out patterns. Without feedback the laser maintained position. See Scott, William B. "RME Spacecraft Demonstrated Precision Tracking and Pointing," \textit{Aviation Week \& Space Technology}, June 17th, 1991, p. 204.
$10^2 J/cm^2$ range. Thus, the ability to provide atmospheric compensation of high intensity laser beams in important, yet problematic.\textsuperscript{17}

The 10 to 100 J/sq-cm figure quoted refers to the total energy moving through the atmosphere. Thus, the threshold of 100 J/sq-cm would be achieved in one second by a 100 W/sq-cm laser. Thermal blooming represents another source of doubt surrounding ground-based lasers. It may be overcome with enough technology, but it might also be impossible to predict.

Significant thermal blooming begins at 0.19 W/sq-cm and exceeds estimated adaptive optics ability to compensate at 340 W/sq-cm.\textsuperscript{18} At this higher threshold, thermal blooming becomes too large an effect to compensate for with predictive models. We will use this value as our limit, making the assumption that science of atmospheric modeling does not achieve a new breakthrough. Since most of the atmosphere is at low altitudes, I make the simplifying assumption that the limit applies at the surface of the mirror, regardless of whether the beam is expanding or focusing as it moves through higher altitudes.

Thermal blooming compensation requires technology that is not yet available and may never be available. They rely on models of the atmosphere and producing results with them every 0.1 sec.

### 7.2.5 Laser Focusing

One question that arises is how can the laser mirror be focused to a point at the target range (ignoring the diffraction limit for a moment)? The distance between the satellite and the laser mirror is constantly changing (except for GEO satellites). If the mirror were focused to a particular range, the diffraction limit on the beam diameter would be:

$$Diameter \approx \frac{\lambda L}{D}$$

\textsuperscript{17}APS Study, pp. S104-S108.
\textsuperscript{18}APS Study, p. S106.
<table>
<thead>
<tr>
<th>Orbit Altitude</th>
<th>4m Mirror Adaptive Optics</th>
<th>10m Mirror Adaptive Optics</th>
<th>10m Mirror No Adaptive Optics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(\frac{\lambda L}{4m})^2$</td>
<td>$(\frac{1.22\lambda L}{10m})^2$</td>
<td>$(\frac{1.22\lambda L}{D})^2 \times \left[1 + \left(\frac{D}{r_0}\right)^2\right]$</td>
</tr>
<tr>
<td>LEO: 200 km</td>
<td>0.0037 $m^2$</td>
<td>0.0006 $m^2$</td>
<td>5.95 $m^2$</td>
</tr>
<tr>
<td>ULEO: 1500 km</td>
<td>0.209</td>
<td>0.0335</td>
<td>335</td>
</tr>
<tr>
<td>SSO: 20,232 km</td>
<td>38.1</td>
<td>6.09</td>
<td>60,900</td>
</tr>
<tr>
<td>GEO: 35,863 km</td>
<td>120</td>
<td>19.2</td>
<td>192,000</td>
</tr>
</tbody>
</table>

Table 7.1: Beam Areas for 4m and 10m Diameter Mirrors

But if the laser beam light were parallel then the beam diameter would be:

\[
Diameter \cong D + \frac{\lambda L}{D}
\]  

(7.3)

In order to remain focused to a point, wouldn’t the mirror constantly have to change its shape? The answer is no. By shifting the position of the telescope mirrors slightly, the focus can be shifted without re-shaping the mirrors themselves.\(^{19}\)

Adaptive optics will probably become widespread throughout the technically developed world. This is because they are a useful astronomical tool. But astronomers will not be interested in high powered adaptive optics. That will require continued research in the U.S.

### 7.2.6 Laser Beam Area

Now that we know the effects of adaptive optics and mirror area, we can compute the beam area given a varying set of assumptions. The varying assumptions are whether or not adaptive optics are working, and whether or not the beam is focused on the target, whether or not thermal blooming can be overcome (this requires working adaptive optics).

For focused mirrors, the beam area is determined by the diffraction limit. That is, because the mirror is focused to a point at particular range, it is possible for the beam area at the target to be smaller than the mirror area, even after accounting for

\(^{19}\)Conversations with Dr. Myron Lecar and Peter Nisenson, Harvard Astronomical Observatory, Harvard University, Cambridge, August and September, 1991.
diffraction. Equations 7.1 and 7.2 describe the beam area at the target for focused mirrors. The beam areas at various ranges are listed in Table 7.1. The three leftmost columns represent different assumptions: a 4 m laser mirror with working adaptive optics, a 10 m with adaptive optics, and a 10 m mirror without adaptive optics.

7.3 Laser Shields

In this section I determine to what extent satellites can be shielded from laser attack. Laser shields can defend in one of two ways: by vaporizing and absorbing energy, or by radiating energy back into space.

When defending a satellite against a ground-based laser, ablative shields are of little use. The attacker simply attacks the target every time it passes overhead. Eventually, the shield will be vaporized away and the satellite destroyed. The relative fuel consumptions works for the laser and against the target in this case: ablative shielding must be put into orbit, while laser fuel is consumed at ground level. So now we turn to radiating heat shields.

Satellite Thermal Capacity

In space there is no gas or water to absorb heat and carry it away. The only way for a satellite to shed thermal energy is to radiate it away. Materials vary in their ability to reflect and radiate thermal energy. Good reflectors are generally bad radiators (white bodies), and bad reflectors are good radiators (black bodies). Thermal radiators are made from black bodies. The total energy a black body radiates is given by the equation:\(^20\)

\[
\text{Energy (J/sec - cm}^2) = \sigma T^4
\]  

(7.4)

where \(\sigma\) is a constant (5.672 \times 10^{-12}), T is temperature in degrees Kelvin,\(^21\) and

\(^{20}\)Weisel, p. 246.

\(^{21}\)One degree Celsius equals one degree Kelvin, but the temperature scales have different starting points: zero degrees Centigrade is 273 degrees Kelvin

209
Energy is in Joules per sq-cm per second or Watts per sq-cm.

Current satellites have to reflect or radiate the Sun's light as they orbit the Earth. Solar intensity around the Earth's is 0.1371 \text{ W/sq-cm}. The Earth also radiates solar energy into space, and consequently onto the satellites in LEO. This radiated energy value is 0.0339 \text{ W/sq-cm}. This is based on an average Earth temperature of 278 degrees Kelvin, and using the radiated energy equation.\textsuperscript{22}

One might ask why the Earth's value is less than the Sun's since the Earth is in thermal equilibrium. Shouldn't it be radiating out as much as it receives? The answer is that the Earth receives energy based on its cross-sectional area ($\pi r^2$), but radiates it back based on its surface area ($4\pi r^2$), thus the value is reduced by a factor of four. This leaves it at $0.1371/4 = 0.0342$ \text{ W/sq-m}. The remaining difference (between 0.0342 and 0.0339) probably can be accounted for by errors introduced by assuming a uniform Earth temperature.

Thus, satellites must shed—in addition to any heat generated by its operation—a total of 0.1710 \text{ W/sq-cm} while in orbit. If a satellite is in thermal equilibrium, we can determine its temperature. Assuming that it is a sphere (and therefore that its surface area is four times its cross-sectional area) we can compute its temperature:\textsuperscript{23}

$$Temperature = \left( \frac{0.1710 \text{ Watts/cm}^2}{4\sigma} \right)^{1/4} = 294 \text{ K}$$

or 22 degrees Centigrade, a little above room temperature.

A dose of a few J/sq-cm would probably overload most spacecraft's ability to shed heat. U.S. estimates of the necessary fluence to kill Soviet satellites range from 2 to 10 Watts/sq-cm.\textsuperscript{24} But what is the capacity of a heat shield to shed heat? This question is addressed in the next section.

\textsuperscript{22}Weisel, p. 247
\textsuperscript{23}A similar calculation is made in: Weisel, p. 246, but for an Apollo capsule far from Earth.
7.3.1 Laser Heat Shields

The best shield is a plate of Tungsten, a metal with a very high melting temperature: 3422 C or 3695 K. Most metals begin to fail mechanically when they get within 10% of their melting temperatures,\textsuperscript{25} so the shield cannot get hotter than 90% of 3695 K, or 3326 K, and remain mechanically sound. Plugging 3265 K into equation 7.4, we get a maximum radiation capacity of 694 W/sq-cm. Also, Tungsten is 50% reflective under intense laser light.\textsuperscript{26} I estimate the emissivity of Tungsten at 3300 K is 0.43.\textsuperscript{27} This gives us a total radiative capacity of $694 \times \frac{1}{0.5} \times 0.43 = 597$ W/sq-cm.

If we were to place a Tungsten plate between an ASAT laser and a satellite, it would radiate energy back toward Earth up to this limit of 597 W/sq-cm. If the satellite were well insulated from the plate, no laser energy would reach the satellite for some time. Multi-layer insulators have a thermal conductivity of 0.00029 W/m-K\textsuperscript{28} or 0.0000029 W-cm/sq-cm-K. If the insulating layer is one cm thick, and if the satellite is at 500 Kelvin,\textsuperscript{29} and the temperature difference is 3326 K minus 500 K equals 2826 K, then the conductivity is $0.0000029 \times 2895 = 8.20$ milli-Watts/sq-cm. The satellite can easily dissipate this kind of energy without a significant rise in operating temperature.

A way to improve on this shield is to increase its reflectivity. The best laser mirrors are built out of dielectric surfaces, which absorb only 0.0001 of the laser light and can withstand flux densities of 20 MW/sq-cm.\textsuperscript{30} These would make ideal heat

\textsuperscript{25}Metals within 10% of their melting points exhibit "creep." Creeping is a plastic deformation of the material under stress, that is, the metal loses its elastic properties (conversation with L. Tatistcheff, Materials Science Engineer, Digital Equipment Corp.). Over time, the metal will eventually fail under stress if it is hot enough to creep.

\textsuperscript{26}APS Study, p. S125.

\textsuperscript{27}The emissivity of Tungsten at 0.65 $\mu$m is 0.43 (see CRC Handbook of Chemistry and Physics, 72nd Edition, p. 10-285.) We can determine the peak wavelength of radiation emission at 3300 degrees by using the following equation: $\lambda_{\text{max}} = 0.00002897/T$ (see Weisel, p. 246). The wavelength of maximum emission at 3300 degrees Kelvin is $0.87 \mu$m. This seems close enough to allow us to use the 0.43 figure.


\textsuperscript{29}Most metals in space under solar illumination have an equilibrium temperature clustered around 500 K (see McMordie in Wertz, p. 382). I chose 500 K as an estimate.

\textsuperscript{30}APS Study, p. S125.
shields, except that their amazing reflectivity is only amazing under very limited conditions. Dielectric coatings are tuned to reflect particular light frequencies, at particular polarizations, and at particular angles of incidence.\textsuperscript{31} Their reflectivity can decline drastically with a change in any of these parameters. This makes them unusable as a defensive shield. The attacker in not likely to use a particular frequency, polarization, and angle of incidence for the defender’s benefit.

If dielectrics are out, is there a material that is a good reflector under varying conditions? Yes. Gold is a good reflector, remaining 98\% reflective or more at wavelengths above 0.7 $\mu m$.\textsuperscript{32} These reflectivities remain high at various angles of incidence and polarizations as well.\textsuperscript{33} Gold has a melting point of 1063 C or 1336 K. Plugging 90\% of that value into equation 7.4 gives us an an irradiated energy of 11.9 W/sq-cm. However, the emissivity of Gold is only 0.023 (good reflectors make bad emitters).\textsuperscript{34} The shield could withstand a flux of $\frac{11.9 W/sq-cm}{0.023} \times 0.023 = 13.7 W/sq-cm$. This is worse than our Tungsten shield.

We come to the conclusion that a sheet of Tungsten represents the best laser shield against a wide range of laser attacks. It is capable of withstanding 597 W/sq-cm continuously, while protecting the satellite behind it.

\section*{7.3.2 A Limited Duration Heat Shield}

The current Tungsten shield is designed to hold up under continuous illumination. This makes sense for a satellite in GEO which, if visible to the ground-based laser ASAT at one time of day, will be visible to the laser at all times of day. But what about shielding satellites in the LEO to ULEO range? These satellites are only visible to a particular point on Earth for minutes. Is it possible to build a thick Tungsten

\textsuperscript{31}Musikant, Solomon \textit{Optical Materials}, Marcel Dekker, Inc., New York, 1985, Figure 9.4, pp. 162-165; and Herrit, Gary L. and David J. Scatena “Choose the right mirror for industrial $CO_2$ lasers” Laser Focus World, July, 1991, Table 2, pp. 114 & 118.

\textsuperscript{32}Musikant, Solomon \textit{Optical Materials}, Marcel Dekker, Inc., New York, 1985, Figure 9.4, p. 195.

\textsuperscript{33}Herrit, Gary L. and David J. Scatena “Choose the right mirror for industrial $CO_2$ lasers” Laser Focus World, July, 1991, Table 2, p. 114.

shield that can absorb a higher laser fluence, but for a limited period of time?

To answer this question, we start by determining the necessary energy to heat a shield to 3326 K (the temperature where its mechanical elasticity begins to fail). I will assume a shield thickness of one centimeter. We need to know the specific heat of the shield. The heat capacity of Tungsten is 5.97 calories/degree-mole.\(^{35}\) One mole of SiC weighs 183.92 gm (the atomic weight is 183.92) and there are 4.184 Joules to the calorie. All that works out to a specific heat of 0.1358 Joules/degree-gm. The density of Tungsten is 19.3 gm/cu-cm, so a 1 cm thick shield will weigh 19.3 gm/sq-cm. Thus, the specific heat of the shield expressed in terms of area is 19.3 \(\times\) 0.1358 = 2.62 J/degree-sq-cm.

Now we need the temperature difference needed to reach 3315 K. I assume that the shield has an equilibrium temperature under direct solar illumination of 433 K.\(^{36}\) The temperature difference then is 3326 - 433 = 2893 K. Multiplying this by our areal specific heat, 2.62 J/degree-sq-cm, we get a total energy requirement of 7380 J/sq-cm to overload the shield. Given the shield’s reflectivity of 50%, this means that the shield must be illuminated with a total of 15.2 KJ/sq-cm of energy to reach it’s failure temperature.

This conclusion is based on the assumption is that we can ignore the energy radiated away by the shield as it heats up. Examining Equation 7.4, we see that the radiated energy is a function of the temperature to the fourth power. This means that until the shield gets hot, the level of radiated energy is very small compared to the energy radiated away at 3315 K. The energy radiated away won’t become significant until the shield gets close to failure. We want to know how long it will take to reach the failure point, so I am ignoring energy radiated away before the shield reaches its maximum operating temperature.

---


\(^{36}\)Assuming a solar absorbtivity of 0.50 (based on it high energy illumination reflectance of 50%) and an IR emissivity of 0.43, we can adapt Equation 7.4 to determine equilibrium temperature under a solar energy flux of 0.0342 W/sq-cm: \(T = [((0.171 \times 0.50)/(0.43 \times 5.67 \times 10^{-12}))^{0.25}\) (see McMordie in Wertz, p. 381) This comes to 433 K.
LEO and ULEO Exposure Times

Next we need to determine how long a satellite in LEO and ULEO is visible to a point on the ground that it is passing over. I make several simplifying assumptions here: first, that the satellite passes directly over the laser site; second, that the laser can illuminate the target from horizon to horizon; third, that there is only one laser ASAT; and fourth, that between illuminations (every 12 hours) the satellite has enough time to cool back to its steady state temperature (500 K). In reality, the satellite will never pass directly over the laser site. It is also unlikely that a laser can be built to fire parallel to the surface of the Earth; the engineering difficulties, terrain obstacles, and atmospheric compensation problems will all conspire to make this very unlikely. On the other hand, it may also be possible to use multiple laser sites, handing off the target from one to another. Finally, it may also be possible to use multiple lasers firing together.

Thus, there are reasons to think that this problem could be made harder or easier. The point of this calculation is to simply see if it makes a significant difference. Does a limited duration exposure of LEO or ULEO increase the survivability of the satellite heat shield? If that calculation is not even close, then we needn’t worry about these details.

At a LEO altitude of 200 km, the satellite is visible for 28.34 degrees of the 360 degrees of its orbit, or 0.0787 of its orbital period. The orbital period of a circular orbit at 200 km altitude is 5309 sec (see Equation 4.2). The satellite is visible for 0.0787 \times 5309 \text{sec} = 418 \text{ seconds}. The calculation for ULEO (1500 km altitude) comes to 71.89 degrees, 0.1997 of the orbit, 6959 \times 0.1997 = 1390 \text{ seconds}.

So, in order to direct a total of 15.2 kJ/sq-cm at a target in LEO, the laser must have an output of \( \frac{15.2 \text{kJ/sq}-\text{cm}}{418 \text{sec}} = 36.4 \text{ W/sq-cm} \). To do so in ULEO, it must have an output of \( \frac{15.2 \text{kJ/sq}-\text{cm}}{1390 \text{sec}} = 10.9 \text{ W/sq-cm} \). The limited exposure times of LEO and

---

\(^{37}\)A right triangle is formed by the laser site, the center of the Earth, and the point where the satellite is first visible. The surface of the Earth averages 6378 km from the center, one leg of the triangle. The hypotenuse of the triangle is the distance of the satellite from the center of the Earth, the radius of the orbit, or 200 km plus 6378 km = 6578 km. Thus \( \cos^{-1} \frac{6378}{6578} = 14.16 \) degrees, the angular distance the satellite travels from the point of first visibility on the horizon to directly over the laser site. Doubling this gives a total spherical angular visibility of 28.34 spherical degrees.
ULEO do not increase the shield’s capacity to withstand illumination. The Tungsten shield remain the best.

Summary

We must remember that any satellite is in orbit to perform a function (imagery, communication, navigation, etc.). This function will require the ability to see or transmit through the shield, which, in turn, will require openings in the shield that could sense an attack and close quickly enough to prevent damage. Current U.S. DSP sensors have been hardened against laser attack using special optics and filters.\(^{38}\)

Obviously, shielding satellites from ground-based laser attack would require some engineering. But the additional weight of the shield would not be substantial. A 0.10 cm thick 20 cm by 20 cm Tungsten shield would weigh only 0.772 kg. The point is that shielding a satellite to withstand hundreds of watts per square centimeter is possible—and with today’s technology, not tomorrow’s.

Principle of Satellite Laser Shielding: Satellites can, with some difficulty, but with today’s technology, be shielded to withstand fluences of 597 of Watts/sq-cm.

7.4 Alternative Futures for Laser ASATs

Given the above analysis, what can we conclude about the future of ground-based ASATs? It depends. We can identify a range of alternative futures, each depending on the results of ongoing research. The range is shown in Table 7.2.

Table 7.2 is divided into three sections. Each makes different assumptions about mirror sizes and adaptive optics. Within each section, each row of the table refers to a particular orbital altitude\(^{39}\) and whether or not the target is shielded or unshielded. We then calculate the beam area at the target. Next we use the damage threshold (5 W/sq-cm for unshielded targets and 597 W/sq-cm for shielded ones) to compute


\(^{39}\)I assume that the satellite is at its lowest altitude, that is, directly overhead.
<table>
<thead>
<tr>
<th>Assumptions:</th>
<th>Calculations:</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Orbit Shielded</td>
<td>Beam Area (m²)</td>
<td>Total Power Required</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10m Mirror, No Adaptive Optics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO No</td>
<td>5.95</td>
<td>354 kW</td>
</tr>
<tr>
<td>LEO Yes</td>
<td>5.95</td>
<td>42.3 MW</td>
</tr>
<tr>
<td>ULEO No</td>
<td>335</td>
<td>19.9 MW</td>
</tr>
<tr>
<td>ULEO Yes</td>
<td>335</td>
<td>2.40 gW</td>
</tr>
<tr>
<td>SSO No</td>
<td>60,900</td>
<td>3.62 gW</td>
</tr>
<tr>
<td>SSO Yes</td>
<td>60,900</td>
<td>433 gW</td>
</tr>
<tr>
<td>GEO No</td>
<td>192,000</td>
<td>11.5 gW</td>
</tr>
<tr>
<td>GEO Yes</td>
<td>192,000</td>
<td>1.36 tW</td>
</tr>
<tr>
<td>4m Mirror, Adaptive Optics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO No</td>
<td>0.0334</td>
<td>1.99 kW</td>
</tr>
<tr>
<td>LEO Yes</td>
<td>0.0334</td>
<td>237 kW</td>
</tr>
<tr>
<td>ULEO No</td>
<td>0.209</td>
<td>12.5 kW</td>
</tr>
<tr>
<td>ULEO Yes</td>
<td>0.209</td>
<td>1.50 MW</td>
</tr>
<tr>
<td>SSO No</td>
<td>38.1</td>
<td>2.27 MW</td>
</tr>
<tr>
<td>SSO Yes</td>
<td>38.1</td>
<td>271 MW</td>
</tr>
<tr>
<td>GEO No</td>
<td>120</td>
<td>7.14 MW</td>
</tr>
<tr>
<td>GEO Yes</td>
<td>120</td>
<td>853 MW</td>
</tr>
<tr>
<td>10m Mirror, Adaptive Optics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO No</td>
<td>0.000595</td>
<td>35.4 W</td>
</tr>
<tr>
<td>LEO Yes</td>
<td>0.000595</td>
<td>4.23 kW</td>
</tr>
<tr>
<td>ULEO No</td>
<td>0.0335</td>
<td>1.94 kW</td>
</tr>
<tr>
<td>ULEO Yes</td>
<td>0.0335</td>
<td>238 kW</td>
</tr>
<tr>
<td>SSO No</td>
<td>6.09</td>
<td>362 kW</td>
</tr>
<tr>
<td>SSO Yes</td>
<td>6.09</td>
<td>43.3 MW</td>
</tr>
<tr>
<td>GEO No</td>
<td>19.2</td>
<td>1.14 MW</td>
</tr>
<tr>
<td>GEO Yes</td>
<td>19.2</td>
<td>136 MW</td>
</tr>
</tbody>
</table>

Table 7.2: Ground-Based Laser ASAT Alternative Future Requirements
Table Notes: Unshielded targets require 5 W/sq-cm to be destroyed. Shielded targets require 597 W/sq-cm to be destroyed. Only 84% of laser energy reaches the diffraction spot used to determine lethal area. Vul: satellite is vulnerable given current laser power of 2 MW. Safe: satellite is safe regardless of improvements in power level. Number: factor by which current laser power must be upgraded; current technology is limited to a factor of 5 increase. Safe (Number): this satellite would be vulnerable, but the mirror limit of 20 Tera Watts ($1 \times 10^7$ more than current lasers) limits the power increase.
the required total power of the laser to destroy the target. Finally, we compute the fluence at the mirror surface.

The conclusions are based first on whether or not the mirror fluence is above any of three thresholds. The 0.19 W/sq-cm threshold is the point at which thermal blooming becomes significant, but can be corrected for with predictive modeling and adaptive optics. The 340 W/sq-cm threshold is the point at which predictive models are unlikely to overcome thermal blooming. The 20 MW/sq-cm threshold is the point at which cooled laser mirrors begin to break down.

If the mirror fluence is above any of these thresholds, then we conclude that the target is safe. That is, it cannot be destroyed under those particular circumstances. If the mirror fluence is below the threshold, and the total power is below 2 MW, then we conclude that the target is vulnerable given current laser power technology. Finally, if the mirror fluence is not a problem, but the total laser power is above 2 MW, we state the factor by which current laser power technology will have to be improved in order to destroy the target.

**No Adaptive Optics**

The topmost section of the table assumes no adaptive optics, and a mirror size of 10 m. In this case, we are not limited by the diffraction limit, but by Equation 7.2. If we multiply out Equation 7.2 we get:

\[
Area \cong (\lambda L)^2 \times \left[ \frac{1}{D^2} + \left(\frac{1}{r_0}\right)^2 \right]
\]

For fixed values of \(\lambda, L,\) and \(r_0,\) beam area is minimized by a large \(D.\) Thus, if adaptive optics are not available, we still want the largest possible mirror diameter, the same result as with the diffraction limit alone. Thus we keep our assumption of a 10 m diameter mirror. Given an \(r_0\) of 10 cm, a wavelength of 1 \(\mu m\) and target altitude of 200 km, the beam area is \(4 m^2\) or \(4 \times 10^4 cm^2.\)

Based on the threshold of 0.19 W/sq-cm for significant thermal blooming, we can conclude that satellites in all orbits, shielded and unshielded are safe because the
thermal blooming fluence threshold is reached at the mirror before the satellite damage threshold is reached at the target. Remember that without adaptive optics, there is no way to compensate for thermal blooming using predictive models. Therefore, in this we section treat the lowest threshold as the important one and do not bother with the higher thresholds. The conclusion here is that without adaptive optics, ground-based lasers are not useful as ASATs against shielded targets at any altitude.

**Adaptive Optics**

In the second section of Table 7.2, we assume adaptive optics are working, but that the laser mirror is limited to current technology of 4m. Here, as with the third section, we list conclusions for all three mirror fluence thresholds. The first applies if we do not compensate for thermal blooming with predictive atmospheric models. The second threshold indicates the probable limits of predictive compensation for thermal blooming. But it might be possible to do better, so we list the third threshold, which is the limit of the cooled mirror surface.

Despite the various thresholds, we can see a definite pattern. Satellites in LEO and ULEO, even with shielding, will be vulnerable. Satellites in SSO and GEO may require shielding, but will remain safe.

In the third section of Table 7.2, we assume a 10m mirror. The conclusions are much the same, but shielding is now definitely required to defend satellites in SSO and GEO. But if very high power lasers become available, even shielded satellites at GEO can be destroyed.

This means that with enough technology and enough laser power, a single laser will be able to melt every satellite in the sky. The only possible exception would be GEO satellites, which are beyond the horizon of the laser. Even then, launched GEO satellites would be vulnerable until they reached their fixed orbit. The question becomes: When, if ever, will this technology become available?
7.5 Conclusions

I conclude that ground-based laser ASATs are simply not worth the trouble. With a large investment in adaptive optics and laser power technology, assuming that these technologies are feasible, and assuming that thermal blooming is not a problem, the U.S. might gain a capability with a marginal improvement over the kinetic kill ASATs of today. It hardly seems worth the effort to produce these weapons. Nor does it seem worth investing the money given the risk that physical limits may make these weapons useless.

If building a ground-based laser would be difficult for the U.S., it will be much harder for another power, even one with impressive technological capabilities. Recently it has been discovered that the Russian test facility thought to be working on directed energy weapons was in fact testing nuclear rockets. For other technological powers as well, it does not seem worth the effort and risk, especially when simpler, more established technologies are available to perform the same task.

From a U.S. defensive perspective, a limited shielding of satellites to the 2 to 10 W/sq-cm level would be prudent to defend LEO and ULEO satellites against a low power laser attacks: the cheap shot. But additional shielding should never be needed. No potential space power is going to make the investment in laser ASATs when much more effective and cheaper alternatives exist. Nor should the U.S. bother to pursue these technologies, they provide no substantial advantage, even if wildly successful.

But to be honest, although ground-base lasers seem a poor investment, one cannot guarantee that it won't pay off. Sudden simultaneous advances in high powered adaptive optics, atmospheric modeling, and laser power might occur. If they do happen, the builder will be able to threaten every satellite in the sky. The lower satellites will become vulnerable first. This presents a dilemma because is it precisely small LEO satellites which are the easiest to defend against KKV ASAT attack. More on this in other chapters.
Chapter 8

The Global Positioning System

Satellite navigation differs from other military space applications in a number of important ways. The Global Positioning System (GPS) is probably the only U.S. space asset which could be used by an enemy during a war. Also, the U.S. lead in this field opens up some additional strategic possibilities which do not exist in the areas of satellite communications and reconnaissance. In this chapter we examine the special nature of the GPS system, address its technical properties, and provide some policy recommendations. We begin with a detailed description of GPS.

8.1 The GPS Constellation

The U.S. currently has two satellite-based navigation systems. Transit was the first and has been in operation for decades, and are still operational today. But Transit has been made obsolete by the new Navstar Global Positioning System (GPS). This is a planned constellation of 24 satellites which emit precisely timed radio pulses. Receivers on the ground can determine their position anywhere on the globe to within 10 meters and velocity to within 3-5 cm/sec.1 As of December 1991, 16 of the 24 orbital slots have operational satellites (2 of the 16 have problems, however), three

have failed in orbit (the GPS launches began in 1978). Orbital lifetime for the latest Block II GPS satellites is 7.5 years.

GPS receivers need to be able to see three receivers simultaneously to get a position fix. A fourth satellite confirms the result. When all 24 slots are operational, a minimum of 5 satellites will be visible anywhere on Earth. Under attack, the GPS system would degrade gracefully. If a visible satellite is destroyed, a 5th satellite confirmation may not be available; if more are destroyed, GPS service may not be available in certain areas for a period of time. During the Gulf War, the Allies were able to use the GPS system quite effectively without the entire constellation being operational. Currently there are 19 operational GPS satellites. They provide coverage (4 satellites visible) 22.5 hours/day on average. GPS coverage is better at the equator than at the poles.

The Russians also have a system in production similar to GPS called Glonass. This system will use 24 satellites in three orbital planes. Because Glonass used three instead of four planes, Glonass coverage is better at the poles than at the Equator. As of March 1990, only eight GLONASS satellites were operational. U.S. aircraft manufactures are considering installing dual capable GPS/Glonass receivers as navigation aids.

---

2Electronic mail posting on Internet by Richard B. Langley, Geodetic Research Laboratory, Dept. of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada E3B 5A3, From: LANG@UNB.CA (Richard Langley), Newsgroups: sci.space,Subject: Navstar GPS Constellation Status (91-02-22),Date: 22 Feb 91 16:37:56 GMT, and Date: 9 Feb 91 16:27:29 GMT.


GPS Coverage

Coverage for GPS is most demanding along the Equator. The GPS constellation will eventually consist of 24 satellites in six SSO planes, inclined at 60.0 degrees, equally spaced around the globe. Each orbit will have four satellites.

The field of view from SSO (20,000 km altitude) is \( \cos^{-1} \frac{6378 \text{ km}}{26378 \text{ km}} = 76 \) spherical degrees. GPS receivers are capable of receiving signals as low as seven degrees above the horizon. Using spherical geometry, we can compute the FOV of a single GPS satellite to be 69.11 degrees. Thus, if the ground tracks of four satellites are within 69.11 degrees of the receiver, the receiver site is “covered.”


9Eastwood, p. 11; and electronic mail posting on Internet by Richard B. Langley, Geodetic Research Laboratory, Dept. of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada E3B 5A3, From: LANG@UNB.CA (Richard Langley), Newsgroups: sci.space, Subject: Navstar GPS Constellation Status (91-02-22), Date: 22 Feb 91 16:37:56 GMT.


11Wertz, pp. 95-96.

transmitted in the clear and an encoded military precision signal (P signal). The C/A signal is normally accurate to 100 ft, but the military has imposed a degradation on the C/A signal which reduces its accuracy of commercial receivers from 100 feet to 300 feet (100 meters). This degradation is called "Selective Availability." During the Gulf War the U.S. did not have enough military receivers so it purchased commercial receivers and then turned off Selective Availability to maximize their accuracy. Now that the Gulf War is over, Selective Availability will be turned back on. It is normally U.S. policy to leave Selective Availability on all the time.

Selective Availability is turned on in peacetime for two reasons. The policy is intended to make it more difficult to access the P signal.\footnote{Philip J. Klass, "Inmarsat Decision Pushes GPS To Forefront of Civil Nav-Sat Field," \textit{Aviation Week & Space Technology}, January 14th, 1991, pp. 34-35.} Part of the C/A signal is used to synchronize with the encoded P signal. Without Selective Availability, one has access to the encoded P signal. With Selective Availability on, additional complexity is introduced because the synchronization part of the C/A signal is randomly shifted in time. The other reason is that military GPS need to train with encoded signals, keeping Selective Availability on in peacetime allows them to train using the encoded P signal.\footnote{"After the War: Who Will Get Accurate Navstar Data?" \textit{Science}, Vol. 251, March 1st, 1991, p. 1013.}

\subsection{The Glonass Satellite Navigation System}

The only competing system is the Soviet Glonass system. It is basically similar in design to the GPS system. But it is far from completion. Since 1982 the Soviet Union has launched 32 Glonass satellites, but only eight are currently operational. The full constellation calls for 24 operating satellites which the U.S.S.R. was expected to complete in 1995\footnote{Philip J. Klass, "Inmarsat Decision Pushes GPS To Forefront of Civil Nav-Sat Field," \textit{Aviation Week & Space Technology}, January 14th, 1991, pp. 34-35.}. With the recent break up of the Soviet Union, it seems unlikely that it will ever be completed.

The aviation community was considering using a combination of GPS and Glonass receivers for two functions: mid-course traffic control and precision bad weather land-
ing aids. The International Civil Air Association (ICAO) has recently adopted GPS as the basis for its Future Air Navigation System (FANS). This is a plan to equip all major airliners with GPS receivers and satellite communications. Air traffic controllers would be certain of aircraft locations over the Atlantic and Pacific oceans, where no radar information is currently available. This would allow controllers to allow planes to take more direct routes rather than channeling them into traffic lanes (as it done currently.) They could also allow planes to ply closer and to change their altitude more quickly.

The second aviation application is in precision landing approaches. GPS is being suggested as an alternative to the planned Microwave Landing System (MLS). The deciding body in the U.S. is the FAA. They need a global system with high accuracy and reliability. Using differential techniques (more on this later) the accuracy problem was solved, leaving only the reliability question. In order to be used for landings, the system would have to reliable in three dimensions, even if one or two satellites failed. With GPS alone, this was not the case. The Inmarsat corporation is planning to add GPS-like emitters to its communication satellites to allow navigation using GPS over the oceans. The Inmarsat satellites will provide a backup in case a GPS satellite fails. But the communication satellites are in geosynchronous orbit, and would not be able to broadcast to higher latitudes. But this reliability problem would have been solved if the Glonass system were also working. Glonass would have provided a global backup to the GPS system. But with recent uncertainties about the future of Glonass, the aviation community has decided instead to use the Microwave Landing System (MLS) for bad weather approaches.16

8.2.2 Absolute Accuracy Now Available

So what is the accuracy available to an enemy of the U.S.? Selective Availability was also intended to prevent unauthorized users from getting 10 meter accuracy. That is, in time of war, the Pentagon did not want the enemy to use GPS receivers against

---

our own forces. If the Glonass system is built, its accuracy is roughly equivalent to the GPS system with Selective Availability turned on (100 meters). In addition, the third generation of Inmarsat satellites will emit GPS signals of their own to act as check on received GPS data. These signals will be only slightly more accurate than GPS with Selective Availability turned on.\textsuperscript{17} Further, the Inmarsat communications constellation is not large enough to provide GPS data alone.

So it would seem that the U.S. can give 10 meter accuracy to its users while keeping everyone else at 100 meters accuracy. This is what military planners had expected when they negotiated commercial access to the GPS system. While 100 meter accuracy is of considerable use to enemy forces, it rules out certain high precision military operations. What the planners had not considered was the cleverness of the commercial users of GPS. We now turn to these issues.

\subsection{Differential GPS}

The problem from the U.S. military viewpoint is a new technique called “Differential GPS” (DGPS). DGPS compares the signals between two GPS receivers which can communicate with each other. Since errors in GPS (including Selective Availability) apply to all receivers in a given area, the difference is very accurate. An aircraft using the system to prevent mid-air collisions can determine its relative position to an accuracy of 3-5 meters.\textsuperscript{18} If one of the GPS receivers is in a known location, the absolute position of the other can be determined as well.

DGPS could also be used for military applications. The system is more demanding than GPS, because it requires a receiver at a known location which can communicate with other receivers within a few hundred kilometers. But once these requirements are met, everything the U.S. military can do with GPS, a potential enemy could do with DGPS. Further, this enemy would have accuracy slightly better than the U.S., and with commercially available equipment. DGPS, in effect, bypasses the

\textsuperscript{17}Philip J. Klass, “Inmarsat Decision Pushes GPS To Forefront of Civil Nav-Sat Field,” \textit{Aviation Week \& Space Technology}, January 14th, 1991, pp. 34-35.

errors introduced by Selective Availability and make military applications available to armed forces throughout the world, regardless of their relationship to the U.S.

8.3 A Military GPS Policy

The U.S. military is in a difficult situation. It has created a substantially improved global aviation system which is very useful to both civilian and military users. Currently the system is under military control, but as the number of users increase, more pressure mounts to stop encoding the signal.

In addition, with Selective Availability turned on, scientific users have an incentive to apply their considerable technical talents to developing ways of bypassing the codes—such as differential GPS. Companies also have an incentive to market these devices. This creates an environment in which the effects of Selective Availability are gradually eroded by scientists and engineers the world over. These new devices also provide devices to armed forces which might one day be at war with the U.S. The current policy provides a short term technical edge to U.S. forces. However, in the long run the U.S. can expect to fight forces who have equal access to GPS technology. With declining military budgets, it is tempting to turn the GPS project over to the Dept. of Transportation to run as a civilian resource and to accept that future enemies will have GPS available to them.

The U.S. military could change its policy and fully encode the signal in peacetime, allowing only U.S. military users with the necessary codes to use the system. But this would anger the civilian and deprive the world of a valuable resource. Further, it would encourage others to develop GPS systems over which the U.S. military has no control. The international civilian aviation community has considerable resources. Airports are billion dollar investments, so the costs of building a GPS-like system are not beyond their means. Further, GPS navigation represents a substantial reduction in costs. United Airlines expects to save $300 million per year using GPS navigation over the pacific.19 Inmarsat already plans to include GPS-compatible emitters on

19“United Expects $300 Million in Savings from Satcom” Aviation Week & Space Technology
its communication satellites. If GPS were un-available, it is quite possible that they would be willing to launch a system for the aviation community. Further, because the system would be built with newer technology and with less stringent military requirements, it would probably cost less than GPS did. Alternatively, the aviation community could pay Russia to finish deploying its Glonass system which is already partially orbited. In either case, the result would be that foreign armies could have access to precise satellite navigation.

It is my recommendation that the U.S. walk a fine line. With too little control over GPS, enemies will have access to it. With too much control over GPS, others will develop systems of their own. I propose the following three policies: First, it should make GPS fully available to everyone who wants it. This will discourage the creation of any GPS competitors. Because peacetime is the norm for the U.S. military, civilian users would develop devices to function with the existing uncoded system. Second, it should fully encode GPS signals during wartime. This should deny enemy armies the use of GPS. There will be little time to develop devices to bypass the GPS codes and only hostile armies will profit from such research. Third, the U.S. should make its wartime codes available to the aviation community to minimize the impact on civilian aviation.

It is my belief that these policies maximize the usefulness of GPS in peacetime while discouraging creation of other systems. During wartime, these policies maximize the technological advantage the U.S. military would have over opponents. We now examine some of these conclusions in more detail.

### 8.3.1 Denial of GPS Services to Commercial Users

The first question we have to deal with is: can the commercial community accept a encoding of GPS data? If aircraft controllers begin using GPS for aircraft spacing in landing patterns, or for collision avoidance as sea, or for taxiway location, a denial of GPS services would mean confusion and possibly disaster.
8.3.2 Inmarsat and Codes via Satellite

Inmarsat is an organization which has places a network of communications satellites over the Atlantic, Pacific, and Indian oceans. These satellites are dedicated to aviation and maritime communications. They hope to offer a DGPS service to aircraft and ships using a network of known cites as reference points. DGPS will provide accurate positioning up to few hundred kilometers from the reference cite, provided the craft and a reference cite can communicate with less than 10 seconds delay.20

When Inmarsat begins to offer this service commercially, it will actually have the same problem as the U.S. military: how to prevent unauthorized users from making use of the DGPS signals it will offer. The answer is that codes will be used to allow only valid subscribers to use the service. The code keys will be issued either monthly or daily, and will be distributed on short notice via Inmarsat telephone or telex.21 In other words, access will be controlled via communications satellite.

I would argue that the U.S. could this same technique in time of war to issue codes to valid users. In fact, the U.S. could probably use the Inmarsat system to distribute these codes.

Thus, aircraft navigation over oceans is not a problem if the Defense Department and the Inmarsat corporation cooperate. This leaves the question of aircraft landing aids. But again, Inmarsat services would be available. In other words, if the codes are distributed, aviation would not be effected.

8.3.3 Other GPS Users

One can imagine other uses of the GPS system. GPS is being installed in cars for navigation purposes.22 Emergency rescue teams could use it to find injured hikers. Recently firefighters used a GPS equipped helicopter to locate fires in Oakland. But


not having GPS would simply be a nuisance; all of the tasks would be made harder, but not impossible.

Other users will be disrupted for the duration of the war. Surveyors are learning to use GPS systems.\(^{23}\) Geologists have been using DGPS, combined with a lot of computer number crunching, to determine fault movement. They have reached accuracies down to the millimeter level,\(^ {24}\) even with Selective Availability turned on.\(^ {25}\)

What I am advocating is the analogous to the black outs of World War II. During the war, coast cities were blacked out to prevent enemy planes and ships from using the city lights for navigation purposes. Blacking out a city at night is disruptive, inconvenient, and dangerous. Accident rates increase, and a few people are killed. But people also accept it as a necessity of war.

### 8.3.4 The Possibility of Foreign GPS-like Systems

Now we move on to the question of foreign GPS satellites. It is my contention that as long as the U.S. provides GPS for free, there is little incentive to any other nation to build a GPS-like system. These systems cost billions of dollars and must be continually updated. The latest GPS satellite has an expected lifetime of 7.5 years\(^ {26}\) If the constellation is 24 satellites (21 operational with three backups), this means that the U.S. will have to launch a new satellite every 3.75 months just to maintain the system. Currently, the U.S. is launching satellites every 2 to 3 months to build up the system.\(^ {27}\) Thus, for an individual nation the question becomes: why spend money for a service which is already available? The one reason for buying such a system is to support a military operation which the United States might oppose. I argue that this is not a sufficient reason.

\(^{23}\) Boston, Dennis "GPS for GIS — How Does it Work?" Public Works, April, 1990, pp. 59, 102-103.


\(^{26}\) Aviation Week & Space Technology February 20th, 1989, p. 18.

Critics will point out that Europe and Japan did not have to develop the capability to launch satellites. The U.S. was already providing such a service. And yet these nations invested billions of dollars to get their own boosters. But the reasons for these programs were numerous. Rockets produce national prestige. High technology projects keep the nation's industrial base competitive. But more importantly, these launch services produce economic value. Launch contracts which would have gone to the U.S. can be filled at home. Further, foreign customers can be attracted to bring money in from outside. Launch services becomes an export rather than an import. The Arianne launch service makes a profit.

In the case of satellite navigation however, nothing of economic value would be produced. Charging for the service would be impossible since the GPS is available for free. The system would simply duplicate a service which already exists. Unlike rockets, navigation satellites are not big producers of international prestige. No dramatic pictures of fiery launches are produced. Few new technologies are developed. The only use for such a system would be in a war with the United States.

It could be argued that with newer technology, better accuracy could be achieved, and that the builders of this system could charge for the more accurate service. But how much more accurate does GPS need to be? DGPS is already down to the millimeter level of accuracy. In order to have a potential market, the service would need to find a group which had a need for better accuracy than DGPS now provides, or for fast accuracy better than GPS now provides. Given the large costs of building such a system, it seems that the potential market is limited to militaries which might find themselves in conflict with the U.S.

I said at the beginning of this section that there was little incentive to build a GPS system. The need to fight U.S. forces is that incentive.

If a hostile nation did begin to build a navigation system, we might want to shoot it down. Since building and launching such a system takes years, the ASAT development would not have to be a crash program. We have already built one ASAT system in storage and another in development. But I would argue that continued ASAT development is not necessary until a hostile nation initiates development of
such a system, at the earliest.

8.3.5 Fall–Back Position

Despite all my arguments, it might simply be too difficult or impossible to encode GPS. I believe that it is possible to encode GPS data. The satellites have a feature for encoding the P-code which is currently turned off. As for the C/A code, all GPS satellites currently broadcast using the same frequency. Each satellite uses a different signal encoding. Receivers can filter out a particular signal by using a particular code. Thus, the GPS satellites and receivers, both commercial and military, already have the hardware for encoding and decoding.

Encoding GPS will involve some inconvenience to military users as well. Civilian opponents of Selective Availability suggested that the military further encode the P-signal rather than distort the C/A signal to prevent access to the P-signal. But the military resisted, claiming that the logistical problems of providing every military GPS user with a decoder were too great to justify its use. Thus, encoding GPS may not be worth the additional trouble.

Political obstacles may prevent the U.S. from encoding all GPS signals. The 100 meter accuracy for Selective Availability was a compromise reached between the Defense Dept., the FAA, and NASA. It was felt that 100 meters prevented many military uses of GPS (which it does) while providing a valuable civilian service. The Dept. of Defense may not be able to back out of this deal.

If it becomes U.S. policy to encode GPS during war, then the policy decision should be made now. This would allow time to prepare procedures for distributing code to Inmarsat and to military users. It is less likely that the military will be able to change it policy in peace time. From the civilian perspective, one advantage of encoding all of GPS is war time is that there is little need to implement Selective Availability in peace time. I think if the civilians agencies and scientists were given

higher accuracy now in exchange for disruption during war time, they would consider that a better deal.

But if encoding to too inconvenient for the military, or if civilians want a consistent level of accuracy they can count on, or if it is too difficult to negotiate a new deal, then the current policy of Selective Availability seems best. It limits absolute accuracy to 100 meters, at least for awhile. If Inmarsat is willing to deny subscription services to users who are at war with the U.S., then differential GPS is more difficult to obtain.

8.4 Summary

The U.S. military has created a valuable navigational resource for the entire planet, free of charge. This has discouraged others from developing similar systems because of the large costs involved. If the U.S. denies this service to others, then competitive systems will emerge. Instead the U.S. should decode all GPS signal in peacetime and encode all GPS signal during wartime. This should continue to provide benefits to the civilian world in peacetime, while minimizing the chances of enemy access during wartime. There will be costs and possible aviation accidents during wartime encoding, but these costs seem acceptable given the violent nature of war.
Chapter 9

Further Technical Considerations

In this chapter we explore a number of technical issues, each of which are important to our inquiry, but did not warrant a chapter of their own. These are: satellite inventory, launch sites, detection & tracking satellites, decoys, gun launchers, nuclear weapons, and development timelines.

I begin by listing the current set of military satellites orbited by the U.S. and the U.S.S.R.; I also list the world's orbital launch sites. Next I determine the requirements for detecting and tracking both satellites and ASAT's in space. Then I discuss the effects of decoys on ASAT operations. Then I examine the costs and risks of a space gun as an alternative launch system. I analyze nuclear weapons as potential ASAT systems. Finally, I estimate the time required to develop and test military satellites and ASAT systems.

9.1 Military Satellite Inventory

So what, exactly, are the U.S.'s military satellites and what do they do? Satellites perform a number of military functions: reconnaissance, weather, communication, signals intelligence, early warning, navigation, and geodesy. We discuss each of these functions in turn. The military satellites of the U.S. and U.S.S.R. are listed in Tables 9.1 and 9.2.
<table>
<thead>
<tr>
<th>Function</th>
<th>Designation</th>
<th>Perigee &amp; Apogee</th>
<th>Weight On Orbit</th>
<th>Constellation Size</th>
<th>Inclination</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo Rec</td>
<td>Keyhole (KH-11)</td>
<td>300x1000</td>
<td>11,360</td>
<td>3</td>
<td>98</td>
<td>90 min</td>
</tr>
<tr>
<td>Photo Rec</td>
<td>Advanced KH-11</td>
<td>LEO</td>
<td>16,900</td>
<td>2-3</td>
<td>57, 65</td>
<td></td>
</tr>
<tr>
<td>Radar Rec</td>
<td>Lacrosse</td>
<td>669x687</td>
<td>-</td>
<td>1</td>
<td>56</td>
<td>cp</td>
</tr>
<tr>
<td>Sig Int</td>
<td>Chalet, Magnum</td>
<td>GEO</td>
<td>-</td>
<td>4(?)</td>
<td>0</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Sig Int</td>
<td>Jumpseat</td>
<td>350x39,200</td>
<td>-</td>
<td>2(?)</td>
<td>63</td>
<td>12 hrs</td>
</tr>
<tr>
<td>Ocean Rec</td>
<td>Whitecloud</td>
<td>1,100x1,100</td>
<td>-</td>
<td>8</td>
<td>63</td>
<td>107 min</td>
</tr>
<tr>
<td>Warning</td>
<td>DSP</td>
<td>GEO</td>
<td>910</td>
<td>3</td>
<td>0</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>DSCS II, III</td>
<td>GEO</td>
<td>1150</td>
<td>8-12</td>
<td>0</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>FLTSATCOM</td>
<td>GEO</td>
<td>1045</td>
<td>4</td>
<td>0</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>Leasat</td>
<td>GEO</td>
<td>1318</td>
<td>4</td>
<td>0</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>SDS</td>
<td>250x39,200</td>
<td>-</td>
<td>2</td>
<td>63</td>
<td>12 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>TDRSS</td>
<td>GEO</td>
<td>2,200</td>
<td>4</td>
<td>0</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Nav</td>
<td>Transit-Nova</td>
<td>1,060x1,060</td>
<td>137</td>
<td>4-6</td>
<td>90</td>
<td>109 min</td>
</tr>
<tr>
<td>Nav</td>
<td>Navstar GPS</td>
<td>20,000x20,200</td>
<td>845</td>
<td>18</td>
<td>63</td>
<td>12 hrs</td>
</tr>
<tr>
<td>Weather</td>
<td>DMSP</td>
<td>810x830</td>
<td>1716</td>
<td>2</td>
<td>99</td>
<td>101 min</td>
</tr>
<tr>
<td>Geodesy</td>
<td>Geosat</td>
<td>785x780</td>
<td>-</td>
<td>1</td>
<td>100</td>
<td>100 min</td>
</tr>
</tbody>
</table>

Table 9.1: Deployment of U.S. Military Satellites

<table>
<thead>
<tr>
<th>Function</th>
<th>Designation</th>
<th>Perigee &amp; Apogee</th>
<th>Constellation Size</th>
<th>Inclination</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>km</td>
<td>Degrees</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photo Rec</td>
<td>Kosmos (3rd Gen)</td>
<td>355x415</td>
<td>1</td>
<td>70, 73, 83</td>
<td>90 min</td>
</tr>
<tr>
<td>Photo Rec</td>
<td>Kosmos (4th Gen)</td>
<td>170x350</td>
<td>1</td>
<td>65, 67</td>
<td>90 min</td>
</tr>
<tr>
<td>Photo Rec</td>
<td>Kosmos (5th Gen)</td>
<td>180x270</td>
<td>1</td>
<td>65</td>
<td>90 min</td>
</tr>
<tr>
<td>Sig Int</td>
<td>Kosmos</td>
<td>635x665</td>
<td>6</td>
<td>83</td>
<td>98 min</td>
</tr>
<tr>
<td>Sig Int</td>
<td>Kosmos</td>
<td>850x855</td>
<td>1-</td>
<td>71</td>
<td>102 min</td>
</tr>
<tr>
<td>Ocean Rec</td>
<td>RORSAT</td>
<td>250x265</td>
<td>1-2</td>
<td>65</td>
<td>90 min</td>
</tr>
<tr>
<td>Ocean Rec</td>
<td>EORSAT</td>
<td>425x445</td>
<td>1-3</td>
<td>65</td>
<td>93 min</td>
</tr>
<tr>
<td>Warning</td>
<td>Kosmos</td>
<td>400x40,000</td>
<td>9</td>
<td>63</td>
<td>12 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>Kosmos</td>
<td>790x810</td>
<td>3</td>
<td>74</td>
<td>101 min</td>
</tr>
<tr>
<td>Comm</td>
<td>Kosmos</td>
<td>1,350x1,550</td>
<td>24</td>
<td>74</td>
<td>115 min</td>
</tr>
<tr>
<td>Comm</td>
<td>Molnya 1</td>
<td>400x40,000</td>
<td>8</td>
<td>63</td>
<td>12 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>Molnya 3</td>
<td>400x40,000</td>
<td>8</td>
<td>63</td>
<td>12 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>Raduga</td>
<td>GEO</td>
<td>12</td>
<td>0</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>Gorizont</td>
<td>GEO</td>
<td>12</td>
<td>0</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Comm</td>
<td>Kosmos</td>
<td>GEO</td>
<td>12</td>
<td>0</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Nav</td>
<td>Kosmos</td>
<td>960x1,020</td>
<td>6</td>
<td>83</td>
<td>105 min</td>
</tr>
<tr>
<td>Nav</td>
<td>Kosmos</td>
<td>960x1,020</td>
<td>4</td>
<td>83</td>
<td>105 min</td>
</tr>
<tr>
<td>Nav</td>
<td>Glonass</td>
<td>19,000x19,200</td>
<td>9-12</td>
<td>65</td>
<td>11.3 hrs</td>
</tr>
<tr>
<td>Weather</td>
<td>Meteor 2</td>
<td>940x960</td>
<td>2-3</td>
<td>83</td>
<td>104 min</td>
</tr>
<tr>
<td>Weather</td>
<td>Meteor 3</td>
<td>1,230x1,250</td>
<td>1-2</td>
<td>83</td>
<td>110 min</td>
</tr>
<tr>
<td>Geodesy</td>
<td>Kosmos</td>
<td>1,480x1,525</td>
<td>2</td>
<td>73, 83</td>
<td>109 min</td>
</tr>
</tbody>
</table>

Table 9.2: Deployment of Soviet Military Satellites, 1987
Communication Satellites

Communication satellites provide line of sight radio communication between two points on the ground. Those in GEO can see plus or minus 81 spherical degrees from the point on the Equator the hover over. However, most receivers must have the satellites at least 5 degrees above the horizon in order to function properly.\(^1\) This reduces the maximum GEO communications footprint to 75.3 spherical degrees.\(^2\)

9.1.1 Photo Reconnaissance Satellites

By far the largest and most expensive satellites are the photo reconnaissance satellites. The U.S. Keyhole series of satellites have gradually evolved from simple cameras in space to large near real-time electronic imaging machines. The latest in the keyhole series, the advanced KH-11's (also referred to as the KH-12), cost roughly $500 million each.\(^3\) These satellites can last, with Shuttle re-fueling, up to six years in orbit.\(^4\) These satellite stay as low a possible in order to get the best possible image resolution. Their orbital lifetime is determined primarily by their fuel consumption used to counter-act atmospheric drag. When out of fuel, the satellite orbit decays and eventually the satellite burns up in the atmosphere. Imaging data is collected electronically and transmitted via SDS and TDRSS communications satellites to Washington D.C.\(^5\)

Someone sitting in a basement in Washington can watch events below the satellite almost as they happen. The resolution of the cameras in the KH-12 are at least 12 inches, and it is rumored that with signal processing this can be improved to as little as six inches.\(^6\)

---


\(^2\)The answer is not 76 degrees. One cannot simply subtract, the spherical geometry is more complex than that. See Wertz, pp. 95-96, for equations.


\(^4\)Stares, p. 18-19.


Radar Reconnaissance

One of the main problems with photo recon satellites is that their optical and multispectral sensors don't work through cloud cover. The gap in intelligence is filled by the Lacrosse radar imaging satellite. Because it is using a longer wavelength, the resolution of the images cannot compare with the KH-12. But it can locate tanks through cloud cover, which the KH-12 cannot. This data can also be relayed via SDS or TDRSS back to the U.S.

Signals Intelligence

This is a collection of satellite which passively listen to transmitters, both communication sites and radars, as well as other satellites in orbit. The Jumpseat satellites are designed to spy on the Soviet Molnya communication satellites (note similarity in orbit parameters, see Tables 9.1 and 9.2), but this program is winding down as the Soviets have moved from Molnya to Raduga satellites (in GEO) for their military communications. Some U.S. signals intelligence ("Sig Int") satellites are simply small receivers which piggy back onto the much larger KH satellites. These are injected into orbits of their own once the KH-11 reaches its orbit. Other SigInt satellites sit up in GEO with huge 60 ft antenna to collect their information.

Ocean Reconnaissance

The U.S. Whitecloud satellite program is devoted to ocean reconnaissance. These are clusters of four satellites which passively listen for communication between surface ships. The Soviet electronic ocean reconnaissance satellites (EORSATs) are much the same, although they operate as a single satellite. The more ambitious Soviet program is the radar ocean reconnaissance satellite (RORSAT) which uses a nuclear reactor

8 Klass, Philip J. "NSA 'Jumpseat' Program Winds Down As Soviets Shift to Newer Satellites" Aviation Week & Space technology, April 2nd, 1990, pp. 46-47.
9 Hobbs, p. 55.
to power an on-board radar to actively track ships at sea. The RORSAT reactors have been the object of controversy. Mission duration of the reactors is about 70 days. The designed method of disposal of the large radioactive spent reactor cores is to boost them into higher, and therefore longer lived, 900 km orbits. This mechanism has occasionally failed, leaving the core low enough (250 km) that its orbit decays. Northern Canada was subjected to radioactive debris from one of these reactors which had failed to boost successfully.

Navigation

The U.S. has two satellite navigation systems as the moment. The first Transit, has been in operation for decades. These small satellites were last launched into LEO aboard Scout rockets in 1970 and 1973. They are still operational today, but have been made obsolete by the new Navstar Global Positioning System (GPS). These are a constellation of 24 satellites which emit precisely timed radio pulses. Receivers on the ground can determine their position anywhere on the globe to within 10 meters and velocity to within 3-5 cm/sec. The full constellation has not yet been orbited. For more details see Chapter 8, p. 220.

9.2 Launch Site Locations

Table 9.3 is a list launch sites in the world which have done or can do orbital launches. Note that sites tend to be close to the equator to maximize the advantage of Earth’s rotation. Also note that with the exception of China and the former Soviet Union, all of these sites are coastal. This is because launches over water reduce problems with range safety. That is, falling debris of failed launches is unlikely to do much damage over an ocean. For this reason, all the coastal launch cites are restricted in the azimuth (compass direction) of the launch. For example, Vandenberg can only

---

10Stares, pp. 22-24.
11Hobbs, p. 58.
<table>
<thead>
<tr>
<th>Launch Site</th>
<th>Nation</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Coastal?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vandenberg AFB</td>
<td>USA</td>
<td>34.36N</td>
<td>120.36W</td>
<td>Yes</td>
</tr>
<tr>
<td>Kennedy Space Ctr</td>
<td>USA</td>
<td>28.30N</td>
<td>80.33W</td>
<td>Yes</td>
</tr>
<tr>
<td>Wallops Island</td>
<td>USA</td>
<td>37.51N</td>
<td>75.28W</td>
<td>Yes</td>
</tr>
<tr>
<td>Kourou Launch Ctr</td>
<td>Europe, ESA</td>
<td>5.32N</td>
<td>52.46W</td>
<td>Yes</td>
</tr>
<tr>
<td>San Marco Launch Platform</td>
<td>Italy</td>
<td>2.56S</td>
<td>40.12E</td>
<td>Yes</td>
</tr>
<tr>
<td>Plesetsk</td>
<td>USSR</td>
<td>62.48N</td>
<td>40.24E</td>
<td>No</td>
</tr>
<tr>
<td>Kapustin Yar</td>
<td>USSR</td>
<td>48.24N</td>
<td>45.48E</td>
<td>No</td>
</tr>
<tr>
<td>Tyuratam (Baikonur)</td>
<td>USSR</td>
<td>45.54N</td>
<td>63.18E</td>
<td>No</td>
</tr>
<tr>
<td>Thumba Equatorial Station</td>
<td>India/UN</td>
<td>8.35N</td>
<td>76.52E</td>
<td>Yes</td>
</tr>
<tr>
<td>Sriharikota</td>
<td>India</td>
<td>12.47N</td>
<td>80.15E</td>
<td>Yes</td>
</tr>
<tr>
<td>Shuang-Ch’Eng-Tzu</td>
<td>China</td>
<td>40.25N</td>
<td>99.50E</td>
<td>No</td>
</tr>
<tr>
<td>Xichang</td>
<td>China</td>
<td>28.06N</td>
<td>102.18E</td>
<td>No</td>
</tr>
<tr>
<td>Tai-yuan</td>
<td>China</td>
<td>37.46N</td>
<td>112.30E</td>
<td>No</td>
</tr>
<tr>
<td>Wuzhai</td>
<td>China</td>
<td>38.35N</td>
<td>111.27E</td>
<td>No</td>
</tr>
<tr>
<td>Kagoshima Space Ctr</td>
<td>Japan</td>
<td>31.14N</td>
<td>131.05E</td>
<td>Yes</td>
</tr>
<tr>
<td>Osaki Launch Site</td>
<td>Japan</td>
<td>30.24N</td>
<td>130.59E</td>
<td>Yes</td>
</tr>
<tr>
<td>Takesake Launch Site</td>
<td>Japan</td>
<td>30.23N</td>
<td>130.58E</td>
<td>Yes</td>
</tr>
<tr>
<td>Woomera Launch Site</td>
<td>Australia/USA</td>
<td>31.07S</td>
<td>136.32E</td>
<td>Yes</td>
</tr>
<tr>
<td>Israeli Launch Complex</td>
<td>Israel</td>
<td>31.31N</td>
<td>34.27E</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 9.3: Operational Launch Sites

launch into orbits inclined from 56 to 104 degrees. The Kennedy Space Center is limited to orbits inclined from 39 to 57 degrees.

Of course, these range safety restrictions are self imposed. There is no physical reason why these sites cannot launch over land if necessary. Equipment on the ground might have to be re-positioned and software re-written, but launch into other orbits is possible.

But the military significance of this understandable attention to safety issues, is that almost all launch cites are very vulnerable. Submarine launched cruise missiles, or a surface combatant close off shore, or even a commando raid, could severely damage any of these facilities, putting them out of action.

Of course, current satellite launches are fairly infrequent. In order to have a military impact, any launch denial effort would be useless without a successful ASAT effort. That is, keeping one’s enemy from launching if useful only if he needs to launch satellites; and he will only need to launch satellites if you can destroy the ones already in orbit.

Launch site vulnerability can also be remedied. Launch sites are usually located on a nation’s home territory. Ships, submarines and aircraft could be (and perhaps already are) employed to defend the launch site from attack. The European nations have a problem however. Europe’s sites are in South America and Africa.

A better solution is a mobile or inland launch site. The Pegasus system, a solid rocket launched from a flying B-52, is quite mobile. The U. S. is currently studying an MX based quick reaction launch program which would use the MX missile as a standby system located in the interior of the U. S., ready to launch back up satellites should the need arise.

It seems that commercial day-to-day launches will continue to occur in vulnerable coastal sites for the foreseeable future. But military quick launches to replace damaged satellites are likely to occur from mobile air-launched systems, or ICBM-based launchers deep in the interior.

To sum up then, with the exception of Russia and China, current launch sites are coastal and possibly vulnerable. In the event of conflict in space, they might well
become lucrative targets. Efforts to defend these sites would have to be successful or mobile or interior launch sites adopted.

9.3 Detection Requirements for ASAT Attack

In this section we examine the problem of detecting and tracking target satellites for ASAT attack. As we saw in Chapters 4, 5, and 6, kinetic ASAT has many advantages over its target, but these won’t be of much use if the target cannot be located. This section will answer the following questions: How difficult is it to detect targets and at various altitudes? What resources, on the ground and in space, are required to provide “global” coverage and what time delays are involved?

The problem of detecting and tracking satellites divides neatly into two categories: LEO and orbits above LEO (primarily SSO and GEO). We begin with targets in LEO: 200 to 1800 km altitude.

9.3.1 LEO targets

A single ground based radar can be used to detect and track satellites in LEO.\textsuperscript{13} Because the satellites in LEO orbit so close to the Earth, the primary obstacle to overcome is the Earth itself. The lower the orbit, the more difficult the problem.

First we ask: from a single observation point on Earth what is the field of view (FOV) to the lowest possible orbit (200 km)? Assuming a perfectly spherical Earth, the spherical angle a radar can see up to 200 km altitude is \( \cos^{-1} \frac{6378 \text{ km}}{6678 \text{ km}} = 14.16 \) degrees. Assuming the radar can scan in both directions, the total spherical angle the radar can sweep out is twice this, or 28.3 degrees.

How much of the LEO population will travel through this FOV? The answer depends on the latitude of our site. All current military satellites in LEO have inclinations of 63 to 110 degrees (see Tables 9.1 and 9.2). If our radar were sited at

\textsuperscript{13}For details about radar power and range, see Mehrholz, D. “Satellite Observations with a Single Radar Tracking Station” Re-entry of Space Debris ESA, SP-246, Noordwijk, the Netherlands, 1986, p. 19.
either pole, the satellites with inclinations below 90 - 14.16 = 75.84 degrees would never be seen. But if our radar is based at latitude 60 degrees or less, this should not be a problem. Thus, the first lesson we learn is: do not place the radar near either pole.

Is the radar FOV large enough to see every satellite twice per day, or can the ground tracks of a LEO satellite skip over the radar FOV? Let's assume the extreme case: that the radar is at the Equator and that the satellite is a polar orbit. These circumstances create the largest distance between ground tracks. If we move the radar north or south of the Equator, the satellite tracks move closer together. This is because the ground tracks of a north-south orbiting satellite are similar to the lines of longitude: they move closer together as one move away from the Equator. For example, a satellite with a 90 degree inclination whose ground tracks are 30 degrees apart at the Equator are only 25.9 spherical degrees apart at 30 degrees North and only 19.2 spherical degrees apart at 50 degrees North.\textsuperscript{14}

Can the radar still see everything in LEO from the Equator? Yes. Most LEO satellites have an orbital period of roughly 90-110 minutes. This corresponds to a perigee/apogee average (the elliptical parameter $a$) altitude of 274 km (see equation 4.3, p. 131). In 24 hours the Earth rotates once relative to the Sun, this is 360.986 degrees relative to the stars, or one full rotation plus a bit to adjust for the Earth’s movement around the Sun. In 90 minutes the Earth rotates ($\frac{1.5 \text{ hrs}}{24 \text{ hrs}} \times 360.986 \text{ Degrees} = 22.56 \text{ Degrees}$, in 110 minutes it rotates 27.58 degrees. Thus, the satellite’s ground

\textsuperscript{14}After doing some basic geometry, I derived the following equation for 90 degree inclination ground tracks:

$$\text{Distance Between Tracks (in Spherical Degrees)} = 2 \sin^{-1} \left[ \cos \alpha \sin \left( \frac{e}{2} \right) \right]$$

Where $\alpha$ is the latitude (north or south) and $e$ is the spherical angle of separation of the ground tracks at the Equator.

Why are the ground tracks farthest apart when the inclination is 90 degrees? Pick a point where the ground track meets the Equator. With 90 degrees inclination, the nearest adjacent tracks are east and west of the current track. As the inclination decreases toward 0 degrees however, points on adjacent ground tracks to the north or south can come closer than those due east and west. In the case of 30 degrees between ground tracks east-west, the inclination has to be less than 30 degrees for this to be true. But if the inclination is 90 degrees, this will never be true, regardless of the angular separation between ground tracks (which depends on the orbital period). Thus, the separation between ground tracks is maximized for all cases when the orbital inclination is 90 degrees.
track moves westward (actually the Earth moves under the satellite) 22 to 28 spherical degrees every orbit. It is impossible for the ground track to skip over the radar’s FOV. This means that twice per day, the satellite will pass within the radar’s FOV, once on a north bound pass, once on a south bound pass.

With a higher $a$, the period would be increase, this would increase the Earth’s rotation between orbital passes, and the satellite ground track separation. The high altitude satellite might be able to skip over the radar’s FOV. In order to have a ground track separation of 28.3 degrees (the radar’s FOV at 200km), the satellite must have a 112.9 min period, which results in an orbital altitude ($a$) of 1,359 km.\textsuperscript{15}

As we increase the satellite’s altitude, however, we also increase the radar’s FOV. At 1,359 km altitude, the radar’s FOV becomes $\cos^{-1} \frac{6378 \text{km}}{6378 + 1359 \text{km}} = 34.48$ degrees in each direction for a total FOV diameter of 68.0 degrees. In other words, if we increase the satellite’s altitude to increase the ground track separation, the radar’s FOV increases faster.

Thus, a single radar installation—which is not in extreme northern or southern latitudes—will be able to track all LEO satellites twice a day. The Earth’s rotation and gravitational field conspire to parade all the LEO satellites past our radar installation. The radar is limited by absolute range, however, as we will see in the next section.

How many objects are there in LEO and can they all be tracked? NORAD keeps track of slightly more than 5000 objects in LEO.\textsuperscript{16} This seems like a lot, but if one breaks it down, it becomes a manageable problem. We have determined that all 5000 objects will pass through the radar’s FOV twice per day: once northbound, once

\textsuperscript{15} And if the satellite is to stay permanently out of the radar’s FOV, it must have a period which evenly divides into 24 hours (plus or minus some small corrections for perturbations based on inclination and the Earth’s 23.67 hour rotational period). A two hour period is a good one to pick. The ground tracks are 30 degrees apart (at the Equator) and this evenly divides into 24 hours.

southbound. That comes to 6.94 objects per minute or one object every 8.64 seconds, on average. This does not seem that difficult a problem. Even if the 5000 object were clumped together, parallel computers can track thousands of objects, keeping track of many hypothetical trajectories per object, gradually determining their actual course. Simulations of a similar problem, tracking 10,000 RVs as part of the Star Wars program, have been successfully run at Sandia National Laboratories.17

When it comes to tracking targets in LEO, a single radar (with some powerful computers) is capable of tracking all 5,000 man-made satellites in LEO and providing data to a ground based ASAT to attack them.

9.3.2 GEO Targets

Above 6000 km altitude, NORAD radars become ineffective at tracking satellites.18 Instead, the U.S. uses electro-optical telescopes which are capable of imaging satellites with a diameter as small as meter at GEO altitudes. This minimum diameter scales linearly with altitude. The optical system is called the Ground-based Electro Optical Deep Space surveillance System (GEODSS). GEODSS sites are spaced evenly around the globe in five locations: White Sands New Mexico, Southern Portugal, Diego Garcia in the Indian Ocean, Taegu South Korea and Maui Hawaii.19 Of the GEODSS

17SDI researchers at Sandia National Labs have run SDI simulations during which they used an nCUBE processor to track the flight paths of 10,000 objects in real time. Sensor data was sporadic the machine also was asked to differentiate between RV's and decoys [presumably based on drag, although it doesn't say].

The simulation lasted 430 sec., with 395 sensors scans, and the calculations were completed in 7.5 min. The simulation started with post-boost phase missiles and tracked them through the MIRVing process, which resulted in about 10,000 objects, Tomkins said.

"Data coming in from the sensors is hard to interpret, so you have more than one hypothesis as to course and speed for each warhead ...sensed being calculated at the same time," Camp said. As more data are received, the hypotheses are "thinned" until an acceptable confidence is achieved.


19Hobbs, pp. 79-80.
sites, the furthest from the equator is 41 degrees N, and the furthest apart are 98 degrees longitude. This implies that they each have a field of view of roughly $360/5 = 72$ degrees. A limitation with the GEODSS system is that they only work in good weather and only at night.\textsuperscript{20}

**Ground-Based IR Satellite Observation**

GEODSS look in the visible range, but Infra-Red (IR) capability is being added to them.\textsuperscript{21} Why? GEODSS depend on reflected visible light to detect their targets. If the satellite is painted black it cannot be seen optically, but it will still radiate in the IR spectrum. Can ground-based IR detectors see a satellite which is painted black? The answer, it turns out, depends on the surface temperature of the target object. The surface temperature, in turn, depends on the assumptions we make about the target.

Given the Sun's radiant energy in the Earth's vicinity of 0.1371 W/sq-cm, we can use Equation 7.4 (p. 209) to determine the temperature of the satellite. If the satellite is a perfect black body sphere (100% absorption and 100% emissivity) which conducts heat very quickly, its radiative surface area is four times its cross sectional absorption area.\textsuperscript{22} We can compute the satellite temperature as:\textsuperscript{23}

\[
\left( \frac{0.1371 \ W/\text{cm}^2}{4\sigma} \right)^{1/4} = 278.8 \ K
\]

On the other hand, if the surface which absorbs the sunlight is a poor thermal conductor, then the results are quite different. Black paint on top of an aluminum substrate has a solar absorbitivity of 0.975 and an IR emissivity of 0.874 which results


\textsuperscript{21}Hobbs, p. 80.

\textsuperscript{22}The cross-section of a sphere is a circle of area $\pi r^2$. A conductive sphere can radiate over its entire surface. The surface of a sphere is $4\pi r^2$.

\textsuperscript{23}Wiesel, p. 246.
Fig. 9-2. Planck's Blackbody Radiation Curves as a Function of Wavelength and Frequency [Chen, 1985].

Fig. 9-3. Transmission Characteristics of the Earth's Atmosphere. Transparent regions are referred to as windows in the atmosphere.

Figure 9-1: Infra-Red Emission Diagrams
Figure Sources: Brodsky, R. F. “Defining and Sizing Space Payloads” in Wertz, p. 221.
in a surface temperature of 405 K if no heat is conducted to other shaded portions of the satellite.24 Of course, if the satellite were partially reflective, the skin temperature would be lower and the peak wavelength would be higher, but then it would be visible in the optical spectrum.

Next, we use the following equation to determine the wavelength at which black-body emissions peak.25

$$\lambda_{\text{max in } \mu m} = \frac{2,897}{\text{Temp in degrees Kelvin}}$$

The radiation peaks at 10.4\(\mu m\) at 278.8 K and at 7.15\(\mu m\) 405 K.

One problem with ground-based IR detection is that the Earth’s atmosphere is between the detector and the object. The atmosphere radiates in the IR spectrum at about 273 K. Picking out the additional IR radiation of the object from the foreground radiation of the atmosphere can be difficult. The walls of the instrument can also contribute to the noise level, but the observing instrument can be cooled to prevent this. It is not possible to cool the atmosphere.

IR radiation intensity is a function of temperature. If the satellite is close to the same temperature as the atmosphere, it is invisible. Thus, if the object is at 278 K, then the IR instrument will not see it. On the other hand, if the satellite is at 405 K, then detection is possible. Each temperature radiates at varying intensities at various wavelengths (see Figure 9-1 in Xerox insert). As the temperature increases, the intensity at all wavelengths increases and the peak intensity wavelength becomes shorter. Thus it is possible to pick out a high temperature object from a low temperature foreground. The in the Xerox Figure 9-1, the largest differences between curves occur at shorter wavelengths because the low temperature curves drop off more sharply than high temperature curves. We can use this effect to our advantage. Lead Sulfide detectors are very sensitive in the 1-3.2\(\mu m\) range. There are most sensitive at 3.0 \(\mu m\) and the IR sensitivity drops off almost vertically above 3\(\mu m\).26 In addition, as the

---

24McMordie, Robett K. “Thermal” in Wertz, Table 11-37, p. 382.
25Weisel, p. 246.
26Brodsky, R. F. “Defining and Sizing Space Payloads” in Wertz, Figure 9-6, p. 234.
Xeroxed Insert Figures show, from about 3.0 to 3.2\(\mu m\), the atmosphere transmits IR radiation. Thus, we can compare the intensity of IR radiation at 273 K and 400 K at 3\(\mu m\) to see how much brighter the hotter object is to the detector. Beyond 3\(\mu m\) the detector sensitivity declines, and below 3\(\mu m\) we know that the difference will be greater than that at 3\(\mu m\).

We can calculate the intensity for a particular temperature at a particular wavelength using Plank’s Law:\textsuperscript{27}

\[
Irradiance(\text{in } \frac{W}{m^2\mu m}) = \frac{2\pi hc^2}{\lambda^5(e^{hc/kT\lambda} - 1)}
\]

where \(T\) is the temperature (in K), \(\lambda\) is the wavelength in m, \(k\) is Planck’s constant \((6.6261 \times 10^{-34})\), \(c\) is the speed of light \((3 \times 10^8 m/sec)\), and \(k\) is Boltzmann’s constant \((1.380^{-23})\). Irradiance for 3\(\mu m\) is 1.09\(\times\)10\(^7W/m^2\)–\(\mu m\) at 405 K, and 3.55\(\times\)10\(^4W/m^2\)–\(\mu m\) at 273 K. A difference of a factor of 309.

So it seems that an object at 405 K would be easily visible. But now we encounter another problem. The diffraction limit resolution of a 1m aperture telescope at 3\(\mu m\) at 36,000 km is 108m. Thus the object, although bright, can only be resolved into a pixel which is 100m x 100m at GEO altitudes. So now we need to know how sensitive our IR detector is.

The rule of thumb is that the best IR detectors are limited to a 1\% change in energy level.\textsuperscript{28} The pixel is 100m x 100m or 10,000 sq.m. Let’s assume that the target object is 10 sq.m. If it is at 405 K, it will be 309 times brighter than the background, but it composes only 1/1000th of the viewing area. Still, this is above the 1\% detector threshold by a factor of 30.9. Thus, the object is probably detectable. Even a 1 sq-m object is above the detection threshold, but only by a factor of four.

We conclude that temperature is critical to ground-based IR detection. If the temperature can be brought down, then the satellite fades into the background and becomes invisible from the ground in IR.

\textsuperscript{27} Brodsky, R. F. “Defining and Sizing Space Payloads” in Wertz, p. 220.
\textsuperscript{28} Conversation with Prof. Rechter, Dept. of Physics, M.I.T., March 30th, 1992.
Recall at the beginning of this section we noted that if a satellite could conduct heat to all its surfaces, then it could radiate away most of the solar energy. Space structures are made of metal and as a result they do conduct heat very well. When the Apollo 13 astronauts lost their internal control system, temperatures dropped to 278.8 K because of this effect.\textsuperscript{29} Even a poorly conducting satellite can accomplish the same effect by spinning.

If designers go to the trouble of painting their satellite black to hide it, they can also be expected to ensure it conducts heat well or that it spins. Either of these measures will ensure a low enough temperature that the satellite will not be visible from the ground in IR. Thus, we conclude that high altitude satellites can be hidden from ground-based sensors with some effort.

This is a definite advantage to the satellite attacker. With only ground-based sensors, the defender cannot see the ASAT approaching to attack her target. This invisibility does not apply to the target because the ASAT IR sensor is in effect a space-based sensor, which as we will see below, is effective in detecting objects in space at long range. One might argue that the attacker would need to acquire the satellite initially from the ground before launching her ASAT, and, if high altitude satellites were completely inert, this would be true. But the all the functions of high altitude satellites (navigation, communication, radio interception) require that they transmit information back to Earth. These transmissions give away their position to ground-based radio sensors.

Laser transmitters could be fitted to satellites for transmission back to Earth. Because optical divergence is so small (even from GEO, with a 10 cm mirror, the diffraction limit is on the order of 4 km), it would be almost impossible to detect these transmissions. The latest versions of the DSP satellite have laser transmitters as a backup.

But laser transmitters systems present difficulties. Laser transmitters weigh roughly twice as much as radio systems and use more power than conventional radio transmitters.\textsuperscript{30}

\textsuperscript{29}Weisel, p. 247.
\textsuperscript{30}Davies, Richard S. “Communications Architecture” in Wertz, pp. 488-489. Note that it is the
The position of the receiver must be known with great precision and tracked accurately, which requires complex and heavy pointing mechanisms. This is difficult to do while spinning to retain a uniformly low surface temperature. And finally, the weather must be clear above the receiver.

In any case, both satellites and ASATs can be concealed from ground-based optical and IR sensors. The spacecraft must be designed to be invisible, but the costs of doing so are not substantial. Satellites, however, must go to extreme lengths to transmit information back to Earth without being detected.

**Space-Based IR Satellite Observation**

An alternative system is to use a space-based IR sensor. In this section we discuss the physical requirements of an on-orbit IR scanning system. An astronomical telescope, the Infrared Astronomical Satellite (IRAS) was orbited in 1983 to perform stellar observations. We can use it to get an idea of the capabilities of an space-based IR system. IRAS proved capable of detecting objects in Earth orbit and improved on NORADs optical capabilities by a factor of two.\(^{31}\)

IRAS had an array of 62 IR sensors which scanned the IR band from 7.9 to 116.5 \(\mu m\). From a circular, sun-synchronous orbit of 900 km, the telescope was able to detect objects 0.5m across at GEO altitudes (GEODSS is limited to 1m objects). The scan rate was 1,112 \(\mu\)rads/sec (3.85 arc-minutes/sec). The width of the scan is not explicitly stated, but the IR detectors width varied from 1,309 to 1,454 \(\mu\)rads (4.5-5.0 arcminutes), we'll use the smaller 1,309\(^{\mu}\)rad value.

Using this data we can determine the angular area scanned per second. 1,112 \(\mu\)rads/sec times 1,309 \(\mu\)rads equal 1,455,608sq.-\(\mu\)rads/sec. Dividing by the number of detectors (62) we get 23,478sq-\(\mu\)rads/second-detector.

---

The entire GEO target space is 360 degrees by 30 degrees (orbital drift of objects in GEO is up to 15 degrees in inclination; this creates a band 30 degrees wide). In radians this is 3.29 sq-rads. The IRAS telescope could scan this area in:

\[
\frac{3.29 \text{ rads}^2}{1.455 \times 10^{-6} \text{rads}^2/\text{second}} = 2,260,200 \text{ sec} = 37,670 \text{ min} = 626 \text{ hrs} = 26 \text{ days}
\]

If we were to build a tracking satellite with 6000 detectors (current DSP early warning satellites weigh 910 kg and have 6000 IR detectors aboard, although of a different type to detect high temperature rocket plumes) we could scan \(1.41 \times 10^{-4} \text{rads}^2/\text{second}\). Thus, the entire GEO target space can be scanned by one DSP-like satellite in

\[
\frac{3.29 \text{ rads}^2}{1.41 \times 10^{-4} \text{rads}^2/\text{second}} = 23,356 \text{ sec} = 389 \text{ min} = 6.5 \text{ hrs}
\]

One satellite can do the work of five ground base sites. Further, the ground based sites must wait for good weather, and we do not know how long they take to perform a complete scan. This satellite does the same thing in six and a half hours, any time of day, regardless of weather.

The IRAS telescope weighed 816 kg with 76 kg of liquid Helium to cool the telescope and keep it at 2-10 K, very near absolute zero. The cryogenic Helium supply was exhausted after 10 months in space. Thus we can assume that the 62 detectors required \(\frac{76 \text{ kg}}{10 \text{ months}} = 7.6 \text{ kg/month}\) to keep cool.

The DSP system would require cooling for 6000 detectors. Assuming that coolant usage is linearly related to detector area, and that the IRAS style detectors are used for scanning space, then the coolant consumption goes up by a factor of 100 to roughly

\[\text{[References]}
\]

\[\text{[Notes]}
\]

\[\text{[Footnotes]}
\]

251
7,600 kg per month. Obviously this is too much.

But there is hope for a better solution. New space cooling systems have been developed which do not vent coolant, and which have an expected operational lifetime of 10 years.\textsuperscript{36} The resulting temperatures (65 K) are not as cold as current sensors need (2-10 K), but the possibility exists of better versions in the future. The European Space Agency expects to have an engineering model of a 4K closed loop cooler for space-borne sensors early next year.\textsuperscript{37}

Alternatively, it is claimed that U.S. labs have produced IR sensors which are more sensitive than current IR sensors and which do not require cryogenic cooling.\textsuperscript{38}

The satellite could be in LEO, as IRAS was, and resolve satellites of 0.5m diameter or greater. With a high inclination, half of GEO would be visible at all times, changing every half orbit (period is 103 min, view changes every 51.5 min). Two LEO satellites would be required for total coverage. By “total coverage” I mean that any portion of LEO can be scanned at any given time. It will still require time to scan all of LEO. The problem with LEO is that these satellites might be vulnerable.

A detection and tracking satellite could also be placed in GEO or SSO, looking across to the far side of GEO it could still see satellites 1m diameter or greater. Of course the Earth would block the view directly across. The angle blocked would be $\tan^{-1} \frac{6378}{6378+35,800} = 8.6$ degrees on either side, or 17.2 degrees total. What fraction of the GEO is this? Since the Earth is half way to the other side, its twice the angle the Earth blocks or 34.4 out of 360 degrees. Thus, two satellites would also be required in GEO to provide total coverage. But with the LEO satellite, coverage is merely delayed with one satellite by a matter of minutes. The higher the satellite, the longer the delay. If the satellite were in SSO, full coverage would be delayed by as much as 6 hours, worse than LEO. With a single GEO satellite, 34.4 degrees is permanently out of view. If the launching nation had one ground based GEODSS at home, a single

\textsuperscript{36}Henderson, Breck W. “U.S. Industry Close to Producing Long-Life Space Cooling System” \textit{Aviation Week & Space Technology} April 6th, 1992, pp. 41-43.

\textsuperscript{37}Mecham, Michael “Europeans Pushing Design of Cryocoolers To 4K Levels for Reliable Space Operations” \textit{Aviation Week & Space Technology}, June 1st, 1992, p. 49.

satellite could be launched into GEO on the opposite side of the Earth to provide total coverage, but the ground station would be limited to clear weather night operations.

Having 34.4 degrees (relative to the surface of the Earth) permanently out of view is not as bad as it seems. Any ASAT system making a transition from LEO to GEO would be visible since a Hohmann transfer orbit would move the satellite through 180 degrees relative to the stars. This would be visible to a single GEO satellite for most of its journey. Even if the ASAT were launched in the blind spot of the satellite moving in the same direction as the GEO satellite, its orbital speed would be much larger than the GEO satellite for most of its transfer orbit. It would be unable to remain in the blind spot.

It would be possible, with a very large rocket to perform a direct ascent in the blind spot. The initial Earth's rotation, imparted to the launcher, would have to be canceled with additional rocket thrust. But this form of attack would be useful only against targets in the blind spot.

Thus, a single satellite can see attackers of all GEO and SSO targets except for a blind spot 34.4 longitude across. If the U.S. has no targets to defend in this area, this is not a problem. Otherwise, two satellite would be required.

An additional problem with the single satellite system is scanning time. The estimate above listed total scanning time for a single satellite as 6.5 hours. An ASAT in Geosynchronous Transfer Orbit (GTO) takes 5.15 hours to make the journey. In order to provide warning the time to cover the entire LEO to GEO area would have to be less than this, which means having an single satellite scanning time of 6.5 hours is not sufficient.

Of course, the attacker will not necessarily know where the satellite is looking at a particular time. So the chances that any given attack would be detected are $5.15/6.5 = 79\%$. But to be certain, two GEO satellites would have a combined scanning time of only 3.25 hours, and without a blind spot. This would argue for a two satellite system.

---

39Average orbital radius ($a$) for GTO is roughly 24,000km which comes to an orbital period of 10.3 hours (See Equation 4.2, p. 131). Half an orbit is required to transition from LEO to GEO, which comes to 5.15 hours.
What about the possibility of an ASAT piggybacked onto an existing GEO communications satellite attempting to attack a GEO target? The answer is that it all depends on how far away the target is. If the system is far, then the ASAT will have to increase or decrease its orbital velocity to alter its orbital period.\textsuperscript{40} This is how weather satellites are gradually moved from one GEO location to another. But this process takes days. A single satellite GEO surveillance system would have no problem detecting it.

The more difficult situation is the hostile ASAT which is very close to its target. GEO satellite separation is only 2 degrees. This is only 1,466 km distance between satellites. This distance could be covered very quickly by an ASAT system. But orbital slots are allocated by the International Telecommunications Union and are a precious resource. A would-be attacker would have to obtain an orbital slot very close to his intended target. Obtaining an orbital slot in the desired region is already difficult enough. Getting a particular slot, while appearing to be only interested in a region, seems almost impossible. But it could happen.

I conclude that one needs two DSP-like satellites in GEO for constant coverage with a 3.25 hour scanning time, or one satellite between LEO and SSO to cover SSO and GEO for coverage with a 6.5 hour scanning time, or five ground stations spaced around the globe to provide local night time coverage depending on local weather.

\subsection{9.3.3 Existing DSP Coverage}

The DSP system already provides some space surveillance. DSP is an IR system but not LWIR, it is sensitive to rocket exhausts and can track any rocket maneuver within its FOV. DSP satellites require only 3 minutes to detect launch and other IR observable phenomena and require only 5 only minutes to characterize its flight path.\textsuperscript{41} This is almost as good as seeing the spacecraft itself, as very little change in velocity occurs in space without rocket thrust. But any ASAT inserting itself into

\textsuperscript{40}It is not initially obvious, but an increase in orbital velocity will result in a higher orbit with a lower period, resulting in net movement in the opposite direction of the thrust.
\textsuperscript{41}Covault, Craig. "USAF Initiates Broad Program To Improve Surveillance Of Soviets," AW+ST Jan 21st, 1985, p. 16.
GTO from LEO to attack a target in GEO could be detected by the DSP system. DSP does not provide total coverage. It is limited to scanning the surface of the Earth. If effect it scans a cone of space between it and the surface of the Earth. Thus its LEO scanning area is limited to less than 81 degrees north and south latitude, depending on the orbital altitude. This means a GTO initiated over either pole will not be detected. Only the absence of the ASAT—detected by LEO scanning radars—after GTO is initiated would indicate a possible ASAT attack. This only works with high closing velocity ASATs however as the ASAT hits the GEO ring at 90 degrees. With additional thrust roughly 4.5 km/sec, a co-orbital assault could be made.

Thus, the existing DSP does provide some coverage, but if an attacker is willing to take a very circuitous route, she can reach GEO without being detected by DSP. Some warning would be provided by the radars scanning LEO, but one would not know if the suspect ASAT had moved up to attack or been de-orbited, or changed LEO location and hadn’t be found yet.

### 9.4 Decoys

Decoys represent a significant last defense against ASAT attack. Inflatable decoys designed to emulate the satellite’s signature (with the exception of operating communications satellites) could weigh as little as 1 kg each.\(^{42}\)

We’ve computed the attacker cost advantages of a pop-up ASAT attacking targets in LEO and ULEO (See Table 6.3, p. 182) range from 34.6 to 3.09. If the attacker’s interceptors weigh 4.5 kg, then the attacker could actually afford to target each of the decoys the satellite dispensed and still retain an advantage, or at worst an equal footing at ULEO altitudes, as far as attacking decoys was concerned. That is, the attacker can afford to destroy decoys with interceptors at equal or less cost (in terms of rocket mass required to launch them) than the defender.

Now the careful reader might point out that inflatable decoys are likely to be

---

\(^{42}\)Decoys designed to emulate nuclear RV’s and fool target SDI discriminators while in mid-course are expected to weigh roughly 1 kg each, See APS Study.
far less costly than expensive interceptors. This is true, but the defender must also launch an expensive and heavy satellite in addition to all of these decoys. Unless thousands of decoys are launched, the advantage remains with the attacker.

More important, the defender also has the problem that ascent times to LEO and ULEO range from 3.24 to 13.8 minutes (See Table 6.4, p. 183). Assuming the defender had an early warning system which scanned for ASAT launches over a wide area 24 hours a day, he might not be able to release his decoys in time. Even the U.S. DSP early warning system, the best in the world, requires 5 minutes to characterize the trajectory of a launch and relay it to controllers on the ground.43

Decoys are only effective if released shortly before an attack. If a satellite were to release its decoys once launched as a permanent defense, they would be of little value. Those decoys in LEO would decay much faster than their satellite, quickly separating the target from the decoys. An attacker would have time to study the decoys carefully, looking for a means of discriminating between them. An important advantage of satellite decoys dispensed at the last minute is that until the war starts, the attacker never sees one. Thus, he cannot determine in advance what the decoy's signature, what size will be, or how many a satellite might have. But if decoys are deployed regularly in peacetime, this advantage is diminished. Operational satellites must maneuver to remain on station, decoys do not. Operational satellites transmit telemetry and mission information to the ground, decoys do not. Again, laser transmitters could be used to solve this last problem, at a higher power consumption and a higher weight, but as we mentioned above laser transmitters introduce a set or problems of their own. And the other problems we mentioned still remain.

One could imagine tethering the decoys to the satellite, or using an single large inflatable balloon to present the ASAT with a large target. This large decoy would contain the satellite, but would hide the satellite within it. In this way, the decoy would move when the satellite moved, and would emit when the satellite emitted. But this can be defeated by an area weapon similar to the pellets of the Soviet ASAT.

---

Because of the advantage impacting debris has on a target, the ASAT can afford to spread out its mass over a large area, destroying the entire decoy target area.

Perhaps if the attacker used a large decoy balloon and shielded the satellite as well. Then the ASAT would have to pepper the entire decoy area with pellets dense enough to penetrate the satellite shield. This might work. But as we noted in Section 5.2.5, slow particles, or those greater than a milligram in mass may not be stopable with a shield. Also the satellite would have to be capable of performing its mission while shielded by a hemi-sphere bumper shield and further enclosed in a large decoy balloon. It seems unlikely that this would make for an effective defense.

In LEO and ULEO, decoys are of little help. It is unlikely that the defender will be able to dispense decoys in time. Even if he does, the attacker advantage is such that the attacker can afford to attack all the decoys and still retain an advantage.

Now decoys in SSO or GEO are another matter. Here the attacker advantage is much diminished (even becoming a dis-advantage in some cases). Ascent times are measured in hours not minutes, so an defender would have time to dispense decoys. But this requires the defender to have the surveillance capability to detect and track an ASAT attack. Given such a system, decoys would be a very effective defense mechanism in SSO and GEO.

9.4.1 Decoy Mass

Next we assess the equation of decoy mass. Satellites vary widely in their size. How does this affect the required decoy mass? The one data point I have to go on is that nuclear RV decoys weigh roughly one kilogram. Now assuming that a small satellite volume is roughly similar, I would estimate the decoy mass at 2 kg. The additional kilogram is for mounting hardware, springs to jetison from the satellite, and wiring to allow the jetisoning of the decoy on command.

Because we have to put the decoys on satellites years, even decades before they might be attacked, we don’t know if the ASAT will be kinetic or nuclear. Thus, we should ensure that the decoy separates itself from the satellite by at least 500 km (the lethal range of a nuclear ASAT against a hardened satellite). The most time urgent
scenario for decoy deployment is against a co-orbital attack in LEO. A pop-up LEO attack provides no almost warning, so use of decoys is not feasible.

But a co-orbital attack would take at least half and orbit. LEO orbits are a little as 90 minutes, so a co-orbital attack could take as little as 45 minutes. I assume that 15 minutes are taken up detecting the launch, determining that it is an ASAT attack, and commanding the satellite to launch its decoys. This gives the decoy 30 minutes to achieve a 500 km separation. Assuming that the decoy weighs 2 kg, a 1 kg hydrazine thruster will provide enough separation. Hydrazine is a monopropellant which is used for small spacecraft maneuvers. These engines are very simple, reliable, and perform well even after being on orbit for long periods of time. A 1 kg hydrazine motor will produce 67 kg-m/sq-sec of thrust for 15 seconds. The total package would weigh 3 kg (ignoring spent fuel mass). 67 kg-m/sq-sec divided by 3 kg times 22 sec yields a velocity change of 300 m/s. 30 minutes is 1800 seconds, the decoy would travel 540 km in that time. Thus, a 3 kg decoy/engine package will perform achieve all that we could ask of a decoy.

What about larger satellites like the KH-11 or Milstar? An RV is roughly 1m by 0.1 m in size. Large military satellite dimensions are roughly 10 times this. Assuming that the decoy is an inflatable balloon, the gas volume would increase as the cube of the dimensions, while the surface area would increase as the square. But we don’t know how much of the one kg decoy mass for an RV is devoted to gas and balloon surface materials. As a conservative guess, I am going to say that the decoy for a large satellite is an order of magnitude heavier than for an RV, or 10kg.

If we apply the same mission requirements to this decoy as we did for the smaller one, we can use a 4.1 kg hydrazine rocket with an impulse of 400 kg-m/sq-sec for 22.5 seconds. Assuming a 0.9 kg mounting and spring hardware requirement, the total package would weigh 15 kg. 400 kg-m/sq-sec divided by 15 kg times 22.5 seconds

---

44A co-orbital attack is unlikely to be a nuclear one. If one has a nuclear ASAT, one would assume a pop-up attack profile to attack targets in LEO. But one never knows, I am trying to determine the most stressful case, a nuclear co-orbital attack seems to be that case, albeit an unlikely one.
45Zafran, Sidney “Space Propulsion Systems” in Wertz, Table 17-8, p. 597.
46Zafran, Sidney “Space Propulsion Systems” in Wertz, Table 17-8, p. 597.
yields a $\Delta V$ of 600 m/sec. Multiplying by 1800 seconds we get a separation distance of 1080 km.

Thus, decoys which can achieve at least 500 km separation within 30 minutes of being jetisoned range from 3 kg for small satellites to 15 kg for larger ones.

9.5 Space Guns

In this section we examine an alternative method of launching objects into space: firing them from a powerful cannon. Three specific technologies are currently being researched: coil guns are being studied at Sandia,47 gas guns at Livermore,48 and ram accelerators at the University of Washington.49

They all have the same basic intent: to violently accelerate a payload and a small solid rocket from the surface of the Earth into LEO altitude, then fire the rocket to establish orbit. An ablative shell protects the payload and the rocket from atmospheric heating. These guns are typically planned with an elevation of 30 degrees from horizontal so the payload arrives with some orbital velocity. Because the object receives all its acceleration at the surface of the Earth, the orbital ellipse of the projectile touches the surface of the Earth. Without alteration the projectile will eventually return to the Earth’s surface. In addition, some velocity is lost to friction as the projectile passes through the atmosphere. The orbit must be circularized50 so a solid rocket is launched with the payload.

Coil guns are electromagnetic cannon. A projectile is fired through a series of coils, each of which imparts a carefully timed magnetic push as the projectile passes through. As the projectile accelerates, the coils must be “fired” more quickly, requiring computers to determine the precise timing. This technology seems to be limited

50The eccentricity of the orbit must be reduced to close to zero.
to a 6 km/sec launch velocity. But this is enough to launch a 1,310 kg projectile with a 157 kg payload into LEO. This is a payload percentage of 12%. We confirm this payload percentage with a gun launch simulation in the section immediately below. This implies that the mass of the projectile casing and heat shield is negligible compared to the payload and rocket, or that the 1,310 kg figure quoted above does not include the casing and heat shield. 12% is much better than a liquid rocket (4.12%) or a solid rocket alone (0.575%), see Table 6.2.

Gas guns are elaborate blow guns. They usually consist of two long tubes, the first wider than the second, which are connected together. Dividing the tubes is a metal disc. The projectile is placed in the smaller tube, next to this divider. A piston is pushed down the length of the larger tube, building up tremendous gas pressure. Eventually the disc ruptures, creating a huge hypersonic shock wave which travels down the length of the smaller tube. The projectile is blown out the smaller tube at speeds of 5 to 6 km/sec. Typical artillery muzzle velocities are 3.5 km/sec. Gas guns have fired small projectiles as fast as 12 km/sec.

The newest idea is the ram accelerator. In this scheme, a projectile if fired by a conventional cannon into a tube containing an explosive mixture of fuel and oxidizer, the as the passing projectile compresses the gases, it ignites the mixture. The projectile is moving fast enough that the resulting explosion occurs along the sides and behind the projectile, pushing it forward ever faster. In the final version, several tubes (divided by thin plastic sheets) will be required. Each tube would contain a different fuel mixture to compensate for the increasing projectile velocity. This technology is relatively new. Thus far, launches have only been at 2.6 km/sec.

All of these systems hope to reduce costs to as little as $300/kg, which is about two orders of magnitude cheaper than rocket costs. If they live up to their promise, they might well revolutionize satellite launch. But they have a long way to go. The most mature technologies, gas guns and coil guns, require large systems built into mountain sides to achieve the 30 degrees elevation and to minimize the amount of atmosphere encountered.

---

Gas guns require huge tanks of compressed gas to propel the piston down the length of the tube filled with hydrogen. Its designers claim the system is closed so there is no danger of explosion.

Coil guns would require very large capacitors to store the electrical energy needed to launch large payloads into space. A single shot would consume 33 Giga-Joules of Energy (recharge would take a 55 Mega-Watts power station 10 minutes). With current technology, the capacitor to store this energy would weigh 11,880 metric tons (11,880,000 kg). Designers hope to get the capacitor down to 1,320 metric tons in the future.

Because of the large-scale nature of these technologies, once built, they would launch into a fixed angle of inclination. Thus, separate systems would be required for polar launches versus those in the 60 degree region. The satellite would also have to be capable of withstanding very large accelerations. But this is possible with electronics (with laser guided artillery shells for example). There would in inconveniences involved in using these systems, but the advantage of low cost more than outweighs them.

The next question these would technologies be useful for ASAT launches? Their lack of flexibility in terms of elevation and orbital inclination means that an ASAT would have to wait until the target satellites passes directly overhead to attack it; and even then, the target would have to have the same orbital inclination as the gun. Attacking satellites in other orbital inclination would require waiting for satellites to pass in front of the muzzle of the gun, which might be never. Now if the ASAT has a large rocket launched with it, this would increase the lethal area the gun would cover.

Perhaps a better way of thinking about this is that the initial orbital velocity imparted by the gun would not be useful to the ASAT because it would be unlikely that the target satellite would fly past the natural trajectory the gun launches into. But the LEO altitude would be a help. The ASAT would not have to launch to altitude. Then it becomes a matter of how far the ASAT can fly once at LEO altitude. This, of course would depend on the size of the rocket it was launched with. It would also depend on the amount of time the ASAT was in orbit.
Based on the calculation in the section immediately below, we compute that the ASAT would have 8 minutes of time above 200 km in orbit. This is sufficient time for a solid rocket to accelerate the ASAT in any direction. Assuming a burn time of roughly 3 minutes, ignoring distance traveled during the burn, this leaves a travel time of 5 minutes. The projectile weight 1,310 kg and the KKV ASAT weighs only 4.5 kg, this is a solid rocket payload percentage of 0.34%, which will provide a $\Delta V$ of at least 4 km/sec. 4 km/sec over 5 minutes is 1,200 km. This corresponds to roughly 10 spherical degrees, for a total lethal diameter of 20 spherical degrees. Thus, a gun launched ASAT would have a very large kill zone, and the position of the gun launcher (excepting the poles) would not be significant.

### 9.5.1 Launch Calculation

Let's begin by assuming a 6km/sec launch at a 30 degree inclination from a mountain site at 10,000 feet (3 km). Using a simulation code (See Appendix C) we can compute the trajectory of the vehicle.

To do this we must include a model for atmospheric drag. To determine the deceleration drag forces create, we use the following equation:\(^{52}\)

$$Deceleration \ (km/s^2) = \frac{\rho(kg/km^3) C_d Area(km^2) Velocity^2(km^2/s^2)}{2 \times Mass(kg)}$$

where $\rho$ is the density of the atmosphere, $C_d$ is the drag coefficient, and $Area$ is the cross-sectional area of the projectile. We will use a drag coefficient of 0.14.\(^{53}\) The cross sectional area is roughly 0.51 $m^2$ or $0.51 \times 10^{-6} \ km^2$.\(^ {54}\) $\rho$ varies with altitude, the code uses a table of entries.\(^ {55}\)

---


\(^{53}\)This is the drag coefficient of a V-2 rocket moving faster than March 5 (1.7 km/sec). See Sutton, George P. Rocket Propulsion Elements John Wiley & Sons, New York, 1986, Figure 5-3, p. 100.

\(^{54}\)Henderson, Breck "Sandia Researchers Test 'Coil Gun' For Use in Orbiting Small Payloads" Aviation Week & Space Technology, May 7th, 1990, Insert Figure, pp. 88-89.

The result is that the projectile reaches 200 km altitude 110 seconds after launch, reaches apogee at 335 km 300 seconds after launch, and comes back down to 200 km 480 seconds (8 minutes) after launch.

When the projectile reaches 200 km altitude, its horizontal velocity is 3.3724 km/sec, and vertical velocity is 1.133 km/sec. When it reaches apogee at 335 km, its vertical velocity is zero and its horizontal velocity is 3.57 km/sec. Using our rocket model developed in Chapter 6, we can compute the payload percentage of the rocket needed to insert the projectile into orbit at these two altitudes. Because of the enormous accelerations involved, the rocket must be a solid booster. The payload percentage at 200 km altitude is 11.7%, and at 335 km altitude it is 12.4%. If we look up the payload percentage to reach LEO in Table 6.2 on page 179, we see that mission payload percentage to reach LEO is 4.12% for liquid boosters and 0.575% for boosters. Thus in terms of rocket mass, a space gun represents a savings factor of 3.0 versus liquid boosters to 21.6 versus solid ones. But as we noted above, the actual dollar cost savings are a factor of 100.

9.5.2 Space Gun Infrastructure

We have stated that all current operational U.S. boosters (with the exception of the Space Shuttle) are derivatives of the original Air Force ICBM projects: Atlas, Thor, and Titan. By “derivatives” I mean that the rockets have been incrementally upgraded over the last 35 years. That is, at no point has a rocket been re-designed from scratch. Instead, sub-sections (strap on boosters, rockets motors, and fuel tanks) have been added, improved, or re-designed. This has lead to a continuous improvement in rocket performance over the years.

But as any engineer will tell you, incremental design change limits the types of improvements one can make. Complete re-design of a system can yield improvements which would be impossible to obtain with incremental design. This is because with incremental improvements, the new sub-systems must be backward compatible with old sub-systems. For example, a new upper stage must still attach to the old lower stage. If both stages were replaced in a complete re-design, then the new systems
would have to be compatible with each other, but not with the older systems. The
designer is free to make the new stages any shape, size, and weight she chooses.

The fact that incremental redesign had been the standard method of rocket im-
provement for the last 35 years is testament to the high cost of rocket design. It has
been difficult to justify a completely new rocket design when some improvement is
always available with lower-cost upgrades of existing systems. Rocket builders have
been unable to obtain the funding required for a completely new booster. The most
recent attempt, the Advanced Launch System was cancelled when NASA and the Air
Force were confronted with a total system cost of $15.3 billion.\textsuperscript{56}

With the exception of manned space systems, we have been relying on the gov-
ernment investments in ICBM development in the late 1950's. We are still using the
same boosters built 30 years ago. We have spend money on upgrades, we've improved
them, but we haven't built any new rockets or considered alternative means of getting
objects into space.

When we examine manned space systems, the Saturn V and the Space Shuttle, it is
also clear that we have been living off investments made in the past. The Saturn V has
abandoned, left to decay and collapse. The Shuttle design represents a compromise
of many design requirements with 1970's technology. Many of the original design
requirements are no longer needed, and much new and improved technology has been
developed since the Shuttle was designed.

My point is that because launch system development is expensive (now it is a
multi-billion dollar investment), only governments can afford the large costs and jus-
tify the long term benefits. Whatever infrastructure the government sets up, the
military and commercial users of space will utilize. In effect, we are faced with the
classic dilemma: should we continue to fix our old car, or is it time to buy a new
one? But these cars are multi-billion dollar investments and the new cars are orders
of magnitude cheaper to operate than the old ones.

We now have an opportunity to invest in a new type of infrastructure in space:
gun launchers. These systems might be able to place small objects into space for

\textsuperscript{56}Finnegan, Philip "SDI Dispute Ends" Defense News Sept. 21-27, 1992, p. 16.
100 times less per kilogram than existing boosters. The objects launched by space
guns will have to be able to withstand violent accelerations, so astronauts are not a
possibility. But space guns could launch supplies and fuel for manned systems as well
as satellites.

A space gun would significantly reduce launch costs as compared with rocket
boosters. The savings to the U.S. economy would continue as long as the U.S.
launched objects into space or a superior technology emerges. Space guns would
be a general benefit to the nation.

But more significantly, a space gun would also open opportunities which have
thus far been blocked. Anyone who has been unable to pay the large sums needed to
build and launch large satellites has had to seek terrestrial alternatives. Now smaller
satellite operators with cheaper satellites can participate in the benefits of space. A
space gun would significantly lower entry costs to space.

In fact, increased demand as a result of lower price is crucial to the success of a
space guns because its low costs can only be realized if usage is higher than current
booster demand. This is because substantial investment goes into building the system
in the first place. High usage decreases the cost per kilogram paid toward initial
investment. Operating costs are low compared to rockets because almost the entire
launch system is re-usable. In contrast, expendable boosters are called “expendable”
because they are expended. Only the launch tower remains after rocket launch. All
the rockets motors, fuel tanks and guidance systems are thrown away during the
launch process.

It was this waste that led the original Space Shuttle proponents to claim that
it would be a cheap alternative to expendable boosters for satellite launch. The
Shuttle also lifted humans into space, which increased costs substantially, but the
Shuttle’s designers hoped that the Shuttle’s re-usable nature would more than offset
these costs. Unfortunately, system development costs and time requirements forced
NASA to compromise, and provide only a partially re-usable system. The Shuttle
costs turned out to be higher than expected. After the Challenger disaster, Shuttle
operations were suspended. Eventually, new safety requirements added to Shuttle

265
increased operational costs. For both of these reasons, unreliability and increased costs, the U.S. went back to expendable boosters for most of its satellite launches.

Space Gun designers hope to achieve the cost savings that the Shuttle failed to realize. Space guns are not completely re-usable: the solid-fuelled rocket used to circularize the payload’s orbit is thrown away. But this is a far smaller portion than is thrown away by expendable boosters or even the Shuttle system.

There is a danger that, like the Space Shuttle, a Space Gun will not live up to its promise. In a world of cost overruns and schedule slippage, it is difficult to believe that any large government project will come in on-schedule and on-budget. The danger is that we invest $7 billion in a space gun system that ends up costing as much as incrementally improved expendable boosters. But the space gun does have a factor of 10 to 100 to play with. This is a very large safety margin. In other words, a space gun will have to be much more expensive than now believed in order to be cost ineffective, provided launch demand is high.

But never say “never.” Any space gun proposal must be carefully scrutinized. Certainly we are in no hurry to build such a system given the current military space situation. We can afford to build small prototypes for launching very small payloads and see how they live up to their designers’ predictions.

We currently have three different space gun research efforts currently under way. Each uses a different approach to the problem: electromagnetic propulsion, explosive shock wave propulsion, and compressed gas propulsion. For tens of millions of dollars, we can afford to continue all three efforts until a clear winner emerges. We could even adopt a “launch before you buy” approach whereby each program constructed a small prototype before we selected on system to be built at full scale. This would allow us to take advantage of the benefits of competition.

9.6 Nuclear Weapons

Nuclear ASATs have distinct advantages over kinetic ASATs. Unlike the kinetic kill mechanisms we have been examining, these weapons are lethal over a much larger
Figure 9-2: Kill Radius of a 1 Megaton Nuclear Detonation
Note: The filled circle is Earth. The circles centered around Earth are SSO and GEO orbits. The circles not centered on Earth indicate the kill radius of a one megaton nuclear detonation against unshielded satellites.
When a nuclear weapon is detonated in space, X-ray radiation is the effect with the longest lethal range. About 80% of the total energy of the bomb is converted into X-rays. A satellite with 0.06 inch aluminum surface is vulnerable to an X-ray dose of $10^{-5}\text{cal/cm}^2$. A one megaton weapon will produce this level of X-rays as 24,500 km.\textsuperscript{57}

This is a very impressive number. It means that an ASAT need only climb to 11,285 km to kill targets in GEO. Remember that this is an area weapon: decoys, cool black satellite, and evasive maneuvers will not help the defender. With a hand full of nuclear weapons and some high performance rockets, nuclear weapons weigh hundreds of kg (see next section), an attacker could kill the entire satellite population. Six weapons, set off simultaneously in SSO, could disable the entire GEO and SSO regions as well as most of the LEO region (see Figure 9-2). Two more weapons, one at each pole, set off simultaneously with the other six, would destroy everything else in LEO. One primary drawback of this type of ASAT is that one's own satellites and those of neutral countries would be wiped out along with one's enemy's.

The answer to to this vulnerability is shielding. The radiation dose received by the satellite is:\textsuperscript{58}

\[ X - \text{ray Fluence} (\text{cal/cm}^2) = \frac{6.4 \times \text{Yield}}{R^2} \]

where yield $Y$ is in kilotons and the range $R$ is in km. At a cost of 3% in satellite weight and 4% in satellite cost, the satellite can be hardened to withstand 0.1 cal/sq-cm.\textsuperscript{59} Beyond this level, the curves tend sharply upward, requiring much

\textsuperscript{57}Blair, Bruce Strategic Command and Control, Redefining the Nuclear Threat The Brookings Institution, Washington, D.C., 1985, Table 6-2, p. 206.


more shielding for a given level of protection than is practical. Thus, 0.1 cal/sq-cm is an effective shielding limit.

But this is still four orders of magnitude better than an unshielded satellite. With shielding, the lethal range for a one megaton bomb is reduced to 253 km. But other nuclear effects of one megaton weapon have a lethal range of 550 km.\textsuperscript{60} If the satellites are shielded, nuclear ASATs are a much more limited weapon system. Operators of commercial satellites will, of course, improve performance rather than hedge against the possibility of a nuclear ASAT, and are therefore likely remain very vulnerable.

Even against shielded targets, nuclear ASATs remain very effective because they are an area of effect weapon. Decoys are not very helpful to the target unless they can be placed more than 550 km from the target. Also, an IR homing vehicle capable of precise maneuver at hyper velocities is not required.

\subsection{Nuclear Weapon Cost and Weight}

We cannot determine the cost of nuclear weapons to an emerging nuclear power. Such nation may be willing to pay a high price to develop such weapon (as Iraq has demonstrated). The amount a nation is willing to pay to obtain nuclear weapons is difficult to quantify. Nuclear weapons are not quoted on the world market. But we can, at least, determine the minimum cost: the cost to the U.S. Since the U.S. has one of the largest nuclear production facilities already, the marginal cost of additional nuclear weapons should be lowest here. I doubt that any other nuclear power is able to manufacture nuclear weapons at a cost significantly less than the U.S.

So what is the marginal cost of nuclear weapons in the U.S.? The U.S. 1987 budget for nuclear weapons materials and waste management was $2,953 million.\textsuperscript{61} The total number of nuclear weapons of all types produced that year was 1982.\textsuperscript{62} Dividing we get a rough cost of $1.5 million per warhead in 1987 dollars. Recently

\textsuperscript{60}Blair, Bruce \textit{Strategic Command and Control, Redefining the Nuclear Threat} The Brookings Institution, Washington, D.C., 1985, Table 6-2, p. 206.


\textsuperscript{62}\textit{Nuclear Weapons Databook, Volume I} Table 1.8, p.22.
I've been told that today nuclear weapons cost about $2 million each.\textsuperscript{63} Allowing for five years of inflation, $2 million seems a good estimate for the minimum cost for nuclear weapons.

As for their weight, a 1 megaton nuclear bomb (the B33) weighs 1094 kg.\textsuperscript{64} Since weight is important in launch costs, we want the weapon to weigh as little as possible. We probably don’t need a full megaton yield to destroy a satellite, although the lethal range will drop off. The B61 nuclear bomb can yield up to 500 kilotons and only weighs 382 kg. The B57 yields up to 20 kilotons and weighs 348 kg. It seems that there is a diminishing return to using smaller yields to get lighter bombs. The B61, with a half megaton yield should have a large lethal area, while only weighing 382 kg. We will use this as our nominal nuclear ASAT weight.

\subsection*{9.6.2 Political Implications}

The most significant problem with nuclear ASAT is their political fallout. Nuclear detonations in space are outlawed by the Partial Test Ban Treaty. Use of nuclear ASATs in an otherwise conventional conflict would represent a significant escalation.

To assess the value of nuclear ASATs, one must imagine a specific war scenario. If both space powers are also nuclear powers, it is unlikely that they would resort to nuclear weapons as ASATs. If nuclear weapons are already in use during the war, the arena of space conflict is of little relevance.

If one power is nuclear and the other is not, again the nuclear power is unlikely to use nuclear ASATs to gain an advantage in space (and also risk destroying neutrals) because of political considerations. A good example of this is the Falklands War and Vietnam. In those conflicts, even though soldiers of the nuclear powers involved were dying every day, the use of nuclear weapons was never seriously considered. Nuclear weapons are of little actual value in a conventional war against a conventional power, despite their vast military effectiveness. I believe that the same holds true in space.

True, no people would be destroyed by a nuclear ASAT and lives of soldiers on

\textsuperscript{63}Conversation with Tom Neff.
\textsuperscript{64}Nuclear Weapons Databook, Volume I p. 200.
Earth might well depend on being able to destroy these satellite, but nuclear weapons represent an unambiguous threshold. Once this threshold is crossed, there is no going back. My conclusion then, is that nuclear weapons are very effective (perhaps too effective) against unshielded satellites (which include all commercial satellites). They remain effective killers of shielded satellites, although the ASATs must get to within hundreds of km of their targets. But despite these clear military advantages, their use presents substantial political difficulties.

9.7 Communications Jamming

Communications between satellites consist of three types: uplinks or communications from the ground to a satellite; crosslinks or communication between satellites; and downlinks or communications from a satellite to the ground. Most communication satellites systems consist of a single satellite in GEO, so no cross links are required. But for satellites systems with elements which are not in GEO, like LEO reconnaissance satellites, communications can be crosslinked via satellite to reach ground stations. NASA’s TDRSS constellation, consists of three satellites in GEO, each of which can see each other. They are designed to relay communications from any object in orbit (like the Space Shuttle) to a ground station (like Houston).

Of the three types of communication, crosslinks are the least sensitive to jamming. If the antennas used for crosslinks are directional, then any potential jammer must be placed and held between them. This is next to impossible given the nature of orbital mechanics. For example, two satellites in GEO will remain fixed relative to each other and the surface of the Earth. The line between them will lie in orbits which are all lower and therefore faster than GEO. No satellite on that line (except one next to either satellite or on the Earth’s surface) can maintain a fixed position relative to either satellite. It is possible to position oneself briefly between two orbiting satellites, but impossible to remain there.65

If the antennas are not highly directional, problems still exist for the potential

65With enough rocket thrust, one could stay briefly, but rocket fuel would quickly be exhausted.
jammer. Oxygen in the atmosphere absorbs transmissions around the 60 Giga Hertz range. This is why 60 GHz is the frequency designated for crosslinks by the International Telecommunications Union (ITU). The reduction factor ranges from a 300 at 26,000 feet to 10 Billion at sea level.\textsuperscript{66} Thus, a jammer would have to be both very powerful as well as airborne to be effective.

Downlinks are also very difficult to jam. If the ground receiver is using even a slightly directional antenna, the jammer would have to be next to the satellite or flying above the receiver in order to jam the signal.

There may be certain circumstances where this may be a viable means of jamming downlinks. Recently NASA was moving its TDRSS communications satellite to another orbit. Along the way is passed through the GEO positions of two operational commercial communications satellites. It accidentally interfered with the satellites downlink of television transmission for hours. A hardware error aboard the TDRSS was causing “errant retransmissions.”\textsuperscript{67} Thus, in effect, the U.S. already has many potential GEO downlink jamming satellites on orbit. For more discussion of GEO jamming, see Section 2.6.2, p. 58.

The weakest link in the chain is the uplink. Unless the satellite receiving antenna has very narrow beam width, a ground based jammer will be within its footprint. This seems likely since the larger the footprint, the larger an area the satellite can service. In addition, the satellite user will pick a frequency which transmits well through the atmosphere and will attempt to minimize ground transmission in order the minimize weight, antenna size, and enemy detection. It also seems likely that U.S. military forces will be transmitting near territory controlled by its opponent’s, where a large jammer might be set up. Thus, conditions appear ideal for interference.

During the Gulf War, U.S. officials were worried about uplink jamming: “The existing ultra high frequency satellite communications are ‘incredibly vulnerable’ to


jamming . . . Iraqi troops did not try to jam U.S. satellite communications in the war. 'We escaped . . . That's the best you could say about it.'

But there are two very effective counter measures available to the satellite user. The first of these is to use frequency hopping transmissions. This technique involved moving rapidly between frequencies based on a pre-set coded sequence. If the jammer does not have the code, then he must jam the entire frequency range over which the satellite user is hopping. Thus, the effective jamming power is reduced by a factor equal to the hopping bandwidth divided by the bandwidth need to transmit.\footnote{Vice Admiral Jerry Tuttle, Director of Space and Electronic Warfare for the Navy, quoted in Munro, Niel "Revamped MILSTAR Program Opens Door for Terminal Makers" \textit{Defense News} June 10th, 1991, p. 26.} The bandwidth needed to transmit is a function of the desired data rate. For military methods of transmitting bits the needed bandwidth is to $8/3$ times the data rate in bits per second.\footnote{Davies, Richard S. "Communications Architecture" in Wertz, James R. and Wiley J. Larson (editors), \textit{Space Mission Analysis and Design}, Kluwer Academic Publishers, Dordrecht, Boston, and London, 1991, p. 486.} The bandwidth allocated for military uplink communications is 2 GHz wide. Thus, the reduction in jamming power reduction factor is:

$$\text{Power Reduction Factor} = \frac{2 \times 10^9 \text{ (Hertz)}}{\text{Data Rate (bits/sec)} \times \frac{8}{3}}$$

The data rates for various types of communication are listed in Table 9.4. Thus, the jamming reduction depends on how much bandwidth one wishes to use and how much data one wishes to send. Many frequency hopping systems can operate over the same band since the chances they will be using the same frequency at the same time is low. Satellite communications system are designed to tolerate a certain number of errors (called the bit error rate), so if the hopping transmitters do occasionally interfere with each other, the results can be corrected.

Frequency hopping can be effective, but there are drawbacks. These systems eats up band width and increases the bit error rate slightly. It also requires both
<table>
<thead>
<tr>
<th>Information</th>
<th>Data Rate in Bits per Second</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>64 Thousand</td>
</tr>
<tr>
<td>(Commercial Telephone)</td>
<td></td>
</tr>
<tr>
<td>Color Television</td>
<td>44 Million</td>
</tr>
<tr>
<td>(Commercial Quality)</td>
<td></td>
</tr>
<tr>
<td>Color Television</td>
<td>92.5 Million</td>
</tr>
<tr>
<td>(Broadcast Quality)</td>
<td></td>
</tr>
</tbody>
</table>

**Table 9.4: Communications Data Rates**


the transmitter and the satellite to both know the code in advance to determine the correct frequency hopping pattern. Instead of this system, the U.S. had chosen another alternative for use in its Milstar satellites: adaptive nulling.

This is a technique whereby the satellite receiver senses a jamming signal and uses a computer and an electronically controllable antenna to null out the jammer. That is, the electronics aboard the satellite render the antenna much less sensitive to a particular region of its footprint: the area where the jammer has been detected. This technique can reduce effective jamming power by a factor of 100 to 10,000.\(^{71}\)

Yet another method of defeating jammers is to use laser-based communication. Lasers are not used on commercial satellites because radio systems are lighter for data rates usually handled by communications satellites. Above the rate of 100 Mega bps, laser communications require less weight.\(^{72}\) If the U.S. military were willing to pay the additional weight costs it could have these systems. In fact, the latest version of the DSP satellites do have laser downlinks in addition the their radio links.\(^{73}\)

Lasers are not jammable because their dispersion is so little because their fre-

---


\(^{73}\) Covault, Craig "New Missile-Warning Satellite To Be Launched on First Titan 4" *Aviation Week & Space Technology* February 20th, 1989, pp. 34-40.
frequency is so high. Allocations of frequency among laser communications users is not a problem because users cannot interfere with each other. Lasers provide effectively point to point communications, so a highly directional receiver cannot be jammed unless the jammer is right next to the transmitter. This advantage is also a drawback. The antenna must be highly directional, which means that the satellite has to know where the transmitter is, and the transmitter has to know where the satellite is, before laser communications begins.

There is another drawback. As we have seen in other Chapters, laser light attenuation through clouds and rain is very high. Thus, laser communication to a particular ground site is not guaranteed.

Finally, interception of communications data is of little value if the data are encrypted. Advances in computer technology have made encryption much easier to perform that to break. A small personal computer can now quickly encrypt data in such a way that it could take a supercomputer years to decode. It is for this reason that the National Security Agency had tried to limit encryption technology to keys small enough to be broken quickly by supercomputers. It has also advocated the idea of using encrypted signatures to authenticate the sender without encrypting the data itself.

To summarize then, downlinks and crosslinks are currently safe from jamming. Uplinks are vulnerable, but with either frequency hopping, adaptive nulling, or laser communications, jammers can be thwarted. Adaptive nulling appears to be the choice of the U.S. military, and this seems to be the simplest and most cost effective system. Of course, the ease with which the U.S. can avoid jamming also means that any opponent technologically sophisticated enough to build and launch a satellite will probably also be able to defeat any attempts by the U.S. to jam its satellites.

9.8 Sytsem Development Timelines

It is important to know roughly how long it will take to develop new systems, both offensive and defensive. Large satellite systems in particular, are long lead items. If
<table>
<thead>
<tr>
<th>Space System</th>
<th>Development Time</th>
<th>Warning Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(R&amp;D Start to Operational)</td>
<td>(First Test to Operational)</td>
</tr>
<tr>
<td>Micro Commsats</td>
<td>7 months</td>
<td>none</td>
</tr>
<tr>
<td>Nuclear Tipped ASAT</td>
<td>2 years</td>
<td>4 to 17 months</td>
</tr>
<tr>
<td>GEO boosters</td>
<td>6 to 8 years</td>
<td>none</td>
</tr>
<tr>
<td>Co-orbital radar ASAT</td>
<td>?</td>
<td>3 years</td>
</tr>
<tr>
<td>Pop-up MHV ASAT</td>
<td>10 years</td>
<td>3 years</td>
</tr>
<tr>
<td>Pop-up MHV ASAT</td>
<td>9+ years</td>
<td>unknown</td>
</tr>
<tr>
<td>Complex Military Commsats</td>
<td>10 to 15 years</td>
<td>7 years</td>
</tr>
<tr>
<td>Iridium LEO Comsat System</td>
<td>5 years</td>
<td>2 years</td>
</tr>
</tbody>
</table>

Table 9.5: Space System Development Times

we are to recommend what to do when, we will need to know how long it will take the U.S. and its enemies to develop and field new space systems.

Obviously research and development, by definition, is an unknown quantity. Precisely determining how long it will take a nation to copy an existing system is not knowable with any precision.

Entirely new system research, research being done for the first time, is more uncertain. For example, if the U.S. continues with high powered laser research, we have no idea when, if ever, and effective system will be produced. But again, the time spent thus far on an as yet unrealized project gives us a minimum estimate of the time required for other nations to copy this development, should it prove successful.

In new areas of technology, some things prove much harder to do than originally thought. We live in are world of cost over run and schedule slippage. Some systems never emerge at all, either because they are too costly or because it cannot be done. Fusion power is a good example of this type of project. It has not lived up to the claims made in the 1970's. Technical problems abound, and it is not clear that a useful and clean power technology will ever emerge from this research effort.

Other developments seem to fall from the sky. Someone makes a connection which no one has thought of, takes some off the shelf hardware and produces a revolutionary system in record time. The Orbital Science Corporation developed the Pegasus space launch system in a matter of months with only $50 million in investment. No orbital booster has ever been created so quickly and so cheaply.
But if a particular system has already been built, we can make an estimate as to how long it will take others to develop such a system. We know that the system can be built, because at least one nation has already done so. We also know how long it took that particular nation to do it. This at least gives us an estimate of how long it will take other nations to do the same.

In this section we will catalogue the development times for the following systems: boosters capable of putting payloads into GEO, nuclear tipped ASATs given an existing rocket and nuclear warhead, KKV LEO ASATs, micro communications satellites, large navigation satellites, and large military communications satellite. The results of this survey are shown in Table 9.5. We discuss each in turn.

### 9.8.1 GEO Boosters

If any nation is going to attack hardened satellites in SSO or GEO with either nuclear tipped or KKV ASATs, they will require a booster capable of reaching very high altitudes (tens of thousands of kilometers). It is therefore useful to know how long it might take a technologically sophisticated nation to develop such a system. The following nations currently have this capability: the U.S., the U.S.S.R., China, France through Arainspace,\(^{74}\) and Japan.

We can examine the development of the Ariane 4 rocket and Japan’s H-2 rocket as examples of how long it would take a modern technological power to develop a new GEO capable booster. In the case of the Ariane 4 rocket, development was approved in June 1982, and the rocket first flew in June 1988.\(^{75}\) Development time was six years. The Japanese H-2 development began in April of 1985.\(^{76}\) It is expect to fly in 1993.\(^{77}\) The development time is eight years.

---

\(^{74}\)Arainspace is a consortium made up of the following partners: France, Germany, Belgium, Italy, the U.K., Switzerland, Spain, the Netherlands, Sweeden, Denmark, and Ireland. France has a controlling 58.48%. See Interavia Space Directory 1989-90 p. 302.


Although of less relevance it is interesting to note that the U.S. took roughly seven years to develop its ICBMs. Funding for ICBMs began to increase significantly in 1953, and the first operational Atlas came on line in August 1960 (see Section 10.2, p. 287).

9.8.2 Large Military Satellites

Large military satellites are by far the most complex and expensive satellites in orbit. NASA is the only civilian organization with creates anything comparable. Typical development times for these systems are 10 to 15 years, with a lifetime in orbit of 10 to 15 years.\textsuperscript{78} Complex commercial communications satellite systems can take 10 to 15 years to develop.\textsuperscript{79} The Milstar military communication satellites are state of the art. They will cost over a billion dollars each and are equipped with adaptive nulling to make them jam resistant. The Milstar program began in 1983, the first flight test of components began in 1986, and the system was supposed expected to be launched in 1991,\textsuperscript{80} but has yet flown. Total development time thus far is nine years. Milstar might well take 10 years to develop.

9.8.3 Micro Communications Satellite Systems

Small micro satellites which store messages and forward them later are easy to design because they are so simple. An extendible boom with a weight on the end acts as a stabilization device,\textsuperscript{81} keeping the satellite pointed toward the Earth while it rotates about the axis of the boom. Solar cells are placed around all sides of the satellite so that as it tumbles, each is exposed to sunlight (except when the satellite is in the

\textsuperscript{80}Interavia Space Directory 1989-90 p. 265.
\textsuperscript{81}A bar with a weight on each end (the satellite and the weight at the end of the boom) in a orbit will tend to align itself toward the center of a that gravitational field. This is because the orbit is determined by the center of mass in the middle of the boom. The lower weight orbits a little to slowly to counteract the gravitational pull at its altitude and so is pulled downward (i.e. it tends to remain pointed downward). The high weight is orbiting too quickly to counter the gravitational pull and so tends to remain upward.
Earth’s shadow). A simple battery completes the power system. Omni directional antennas do not require additional stabilization. Micro satellites have been designed and launched in as little as seven months by university students at a total production cost of $180,000.\textsuperscript{82}

As for a complete global communication micro-satellite system, the only example we have is the Iridium system. This project is currently looking for funding, the first launch is expected in 1995, and the system is expected to be operational in 1997.\textsuperscript{83} That is a total development time of 5 years, and a first launch to operational capability of 2 years.

9.8.4 ASATs

It would be good to know how long it took the Soviet Union to develop it's co-orbital ASAT. Unfortunately we don't have access to Soviet decisions on this matter, at least not yet. But we can look at their test history to determine how long it took them to develop a working co-orbital ASAT once they began testing. The first series of tests of their co-orbital system began in 1968 and ended in 1971.\textsuperscript{84} During the three years the appear to have perfected a radar-based version of their co-orbital ASAT which required two orbits from launch to intercept. Presumably after these tests, the Soviet co-orbital ASAT was operational.

A later series of tests, from 1976 to 1982 tested a less-than-one-orbit-to-hit co-orbital ASAT which worked, although the test series of this version was not as successful as the earlier version. An additional innovation which was tired was using an IR homing device. apparently, all of the tests with this device were failures. We can conclude that co-orbital ASAT tests take at least three years, and that innovations such as single orbit attack profiles and IR sensors can take longer and can be unsuccessful.


\textsuperscript{83} Phone conversation with John Windolf of Iridium Inc., Washington D.C., April 27th, 1992.

As for the U.S.'s hit-to-kill MHV ASAT, the contract was awarded in 1977.\textsuperscript{85} The first successful test was in 1984, and the ASAT system was to be operational in 1987, but was canceled.\textsuperscript{86} Development time was seven years. But an additional three years would have been needed to field the system as an effective weapon. Thus, the total development time would have been 10 years. Given that development of such a system could be kept secret until the first test, warning time would have been roughly three years. In other words, if we assume that no system is currently under development, we can estimate it will be at least 10 years before the U.S. will have to face an operational pop-up KKV ASAT. We can expect three years of warning time between test and deployment.

As for the latest KKV ASAT, if we assume that research began after Regan's 1983 Star Wars speech, it's been 9 years so far and the KKV has been built, but thus far not tested. We can assume that it will take the U.S. at least 9 years to have developed an operational KKV ASAT system. The time between first test and operational status is not known because we haven't tested yet.

\subsection{9.8.5 Nuclear ASATs}

We also have some data from the U.S. on nuclear tipped ASATs. Given a working rocket and available nuclear weapons, how long will it take a nation to field an operational nuclear LEO ASAT system? The U.S. fielded two such systems in the 1960's. The Army system, project MUDFLAP, was based on the Nike Zeus ABM. The project was authorized in May 1962 and became operational in May 1964.\textsuperscript{87} Development time was two years. The first test took place only seven months into the program.

The Air Force nuclear ASAT was based in the Thor missiles which were coming back from Europe at that time. Work began in February 1962 and the system was operational in June of 1964.\textsuperscript{88} Development time was two years. The first test took

\begin{NB}
\textsuperscript{85}Stares, p. 206.
\textsuperscript{86}Stares, p. 209.
\textsuperscript{87}Stares, pp. 118-119.
\textsuperscript{88}Stares, pp. 120-123.
\end{NB}
place only four months before being declared operational
Chapter 10

The Politics of Space Missions

In this thesis I propose a U.S. military space policy. The previous chapters have described the technical military realities of space: what physical constraints apply there and what current technology can do there. These have resulted in a set of policy recommendations for the future. Any space policy will encounter the biases of the military services that will carry it out. In this Chapter I describe the political history of space missions. I examine the cultural attitudes of three military services toward space missions: the Army, the Navy, and the Air Force. Because the Marines Corps has almost no space history,¹ it is not considered here. This chapter also discusses other agencies with space missions (the CIA and NASA), but the focus is on the military services because they will be the implementors of military space policy.

The civilian leadership is my intended audience. For them, I wish to illuminate the "lay of the land," both technically and politically. I am not discussing the attitudes of civilian leaders toward space. In the history that follows, I treat them as an external force, acting upon the services and reacting to their decisions. I treat the civilians as external because the civilian leadership makes decisions but does not implement them. Implementation is left to the services, which are tightly knit organizations with cultures that change only slowly. If the civilians are to get done what needs to be

¹The Marine Corps has contributed men to the astronaut program. Probably the most famous of these is John Glenn (now a Senator) who was the first American to orbit the Earth.
done, they will have to take these attitudes into account.

I begin with a discussion of organizational theory and what kind of behavior one might expect from the three services. Then I go on to describe the history of five military space areas: rockets, manned systems, reconnaissance satellites, communication satellites, and anti-satellite systems. Finally I draw some lessons from the history of the U.S. military in space and apply them to the policy recommendations presented in Chapters 1, 2, and 3.

10.1 Organizational Theory

In order to better understand service behavior, I begin with an overview of some useful organizational theories. J. D. Thompson, in his book *Organizations in Action*, states that "the central problem for complex organizations is one of coping with uncertainty." They do this by attempting to control uncertain environmental inputs. This, in turn, leads organizations to grow. In particular, they will attempt to enlarge their domains to include areas that directly impact their major mission. Organizations also like growth because it allows the organization to pay well and to promote its people, which attracts skilled people. So we can expect services to attempt to grow in order to control areas that affect their central activities or missions and to attract desirable members.

Further, in the absence of clear indications of performance, organizations will compare their activities with past performances and with other organization. For the military services, core activities are the creation and maintenance of military forces. Unfortunately, information on those forces’ performance is generally not available, especially in peace time. Lucas and Dawson explain that military organizations measure their current performance by their activities. They compare current activity with past activity: are we doing more of what we do? Individuals and sub-groups within

---

3 Thompson, Chapter 7, pp. 83-98.
the military are evaluated by how much they contribute to, or actually perform, these activities.

Lucas and Dawson point out that the military organizational environment has several unique features. Military organizations are dedicated to maintaining the security of the United States, but security is a very difficult thing to measure. Military suborganizations believe that their activities are contributing to security but tend to focus on maximizing their particular activity rather than constantly re-evaluating their relative contribution to national security. This effect is called "goal displacement." Organizations become natural advocates of their own activity as superior to others' activities. But they believe that they are still maximizing national security. Consequently "... organizational conflict is often all the more intense because it is well-intentioned."

A service's activity level is determined by funding. Consequently, the competition for funds is a major component of the competition between the services. The Constitution leaves the Executive Branch nominally in charge of the military services, but funding must be authorized by Congress. In the all important struggle for funds, groups within services compete and the services compete with each other. Clark notes that the DOD is a very competitive bureaucracy and that this competition is centered on resources. Although the military services are themselves hierarchical organizations, they are embedded in a structure that allows for considerable autonomy. Clark notes that military services can resist instructions from DOD executives.

This competition is often useful to civilian policy makers because for every program advocated by one military group, there is another group within the military that is willing to criticize it. But competition also produces much duplicate effort. Landau argues that overlapping military programs are good because they provide

---

5 Lucas and Dawson, Chapter 1.
6 Lucas and Dawson, p. 13.
7 Lucas, William and Dawson, p. 11.
9 Clark, p. 255.
systems more enthusiastically; competition can promote innovation. Clark states that those services who perceive themselves as losing ground in the struggle for funds will be the most innovative in terms of technology, doctrine, and force structure. These services in decline will seek out new missions and new technologies to improve their position in the competition for funds. On the other hand, the services that are winning the funding competition will procure more systems and improved systems that perform an existing function. That is, well funded services will attempt to get more of what is working for them.

Finally, Steven Peter Rosen provides some interesting thoughts on maintaining a new function within a military service in peacetime. His case studies indicated that in peacetime, military services retain an innovation only if junior officers can make their careers within the newly created sub-organization intended to perform this new function. It is important to bring senior officers into the project to create a career promotion ladder. Without senior leaders, junior officers will be forced into other occupations as they are promoted (if they are promoted), even if they enthusiastically endorse the innovation.

Here is what these organizational theories suggest about service behavior: We can expect the services to attempt to extend their control into areas that affect their core missions. We can expect a strong competition for program funds, with each service sincerely believing that it can best provide security for the U.S. We can expect the services to bypass unfavorable civilian decisions by appealing to other civilians. We can expect dominant services (those receiving increasing funds) to do what they are already doing, only bigger and better. We can expect those services who feel they are losing the funding competition to be highly innovative in their research efforts. Finally, we can expect that any new function or mission will only survive in the long run if senior officers are appointed to head the new organization, thereby creating a career path for junior officers.

---

12 Clark, pp. 258-260.
10.2 Rocket Wars: The Struggle for Access

In order to be a player in space, one needs to get there. Thus, the first step in any space program is to build a rocket. Compared with most military vehicles, rockets are technologically intensive and very expensive pieces of equipment.\textsuperscript{14} Rocket development was a substantial part of the late 1950's defense budget.\textsuperscript{15}

The reasons for developing rockets evolved over time. Initially, rockets were guided missiles designed to deliver conventional munitions over hundreds of miles. Later, they were developed to deliver atomic weapons over thousands of miles. Finally, they were used to launch satellites—and then people—into space. In this chapter, I use the terms ICBMs, rockets, and boosters interchangeably because they perform the same function. They only differ in terms of payload.\textsuperscript{16}

During the late 1940's and throughout the 1950's all three services were engaged in a competition to build their own rockets. The Army and the Navy tried to obtain a role in this new mission area of strategic bombardment, while the Air Force sought to exclude them while also becoming the dominant service in space. Rocket development was expensive, so this competition centered on each service's ability to get funding. All three services developed boosters capable of launching satellites into space. By the early 1960's however, the Navy and the Army had dropped out of the competition to orbit objects, although they continued to develop sub-orbital rockets. Then a new competitor, NASA, joined the fray. By the late 1960's, the Air Force had achieved a monopoly on satellite launchers; but it had lost the man-in-space mission to NASA, a devastating blow from which the space enthusiasts of the Air Force have never fully recovered.

\textsuperscript{14}Rocket engines must lift their payloads without assistance from the ground, water buoyancy, or aerodynamic lift as trucks, ships, and aircraft do.

\textsuperscript{15}In Fiscal Year (FY) 1957, total ICBM/IRBM funding was $1.4 billion (see Table 10.1, p. 296). The total Air Force budget for FY1957 was only $17.6 billion. See Office of the Comptroller of the Department of Defense, \textit{National Defense Budget Estimation for FY1992} March 1991, Table 6-10, p. 96.

10.2.1 Early Rocket Development: The Early 1940's

Struggles among the services for control of guided missile development date back to the end of the World War II. "In June 1944 the Germans started firing their dreaded V (for vengeance) weapons. Although highly inaccurate and soon easily defeated, the V-1 cruise missile terrorized the Allied civilian population, and a clamor went up for the United States to match the enemy's technology."\(^\text{17}\) The V-1 was an early cruise missile, but the V-2 was a true ballistic rocket and it was not easily defeated. German V-1 and V-2 missiles inspired the U.S. Army to develop versions of its own. The General of the Army Air Forces, General Henry H. "Hap" Arnold felt that missiles would revolutionize warfare. "...it was expected that the organization that won responsibility for missile development would gain operational control as well."\(^\text{18}\) In other words, missiles might represent the future of warfare, and the service that gained control of the missiles might be assured a well-funded place on the battlefield of the future.

Immediately, parallel efforts in different branches of the Army lead to competition. Both the Army Air Forces and the Army Service Forces' Ordnance Department began work on guided missiles.\(^\text{19}\) At that time the Air Force was still part of the Army. Originally the Army Air Corps, it became the Army Air Forces (AAF) in June 1941, and would eventually become the United States Air Force (USAF) in 1947. The Ordnance Department of the Army Service Forces (ASF) was to remain part of the "real" Army.\(^\text{20}\) Hereafter, the phrase "Air Force" refers to those branches of the Army that became the Air Force; the word "Army" refers to those branches that were destined to remain part of the Army.

These parallel missile development programs lead senior officers and civilian ad-


\(^{18}\)Neufeld, p. 8.


visors to try to eliminate needless duplication by providing a clear division of responsibilities. In October 1944 an Army directive gave the Army Air Forces control of all air-launched and cruise missiles, leaving the Army Service Forces with ballistic missiles.21 At the time, winged air-breathing missiles (cruise missiles) were considered to be much more practical than ballistic missiles. Consequently, the ASF resisted this division of roles. The early struggles between the Army and Air Force were over development of cruise missiles, despite the directive.

The Navy also began its own missile work and by the close of World War II, the Army and the Navy were far ahead of the Air Force in missile development.22 By 1945, the Army Air Forces were very unhappy about the Army’s other missile projects, which they felt were trespassing on AAF jurisdiction. The Army Ordnance Department had started work on long range guided missiles that were cruise missiles, yet it claimed to be abiding by the 1944 directive. AAF observers looked at Ordnance’s missile designs and saw “wings”, but Ordnance called them “fins.” Both branches appealed for clarification of the 1944 directive as well as for increased authority.23

This set the pattern that was to be repeated several times. Parallel programs lead to directives from higher authority, which lead to arguments between services about the definition of language in the directive, which lead to continued parallel programs, new directives, and so on. Civilian efforts to curb duplication between services were thwarted by their limited control over service research and by the desire

21 Quoted in Beard, p. 22. Joseph T. McNarney, Deputy Chief of Staff, Memo to the Commanding General, Army Air Forces, October 2, 1944: “a. . . . Army Air Forces, have research and development responsibility, . . . for all guided or homing missiles dropped or launched from aircraft. b. . . . Army Air Forces, have research and development responsibility for all guided or homing missiles launched from the ground which depend for sustenance primarily on the lift of aerodynamic forces. c. . . . Army Service Forces, have research and development responsibility for guided or homing missiles launched from the ground which depend for sustenance primarily on momentum of the missile.”

22 Quotes from Neufeld, pp. 18, 26 & 42: “Despite a great deal of activity, little progress was achieved. At war’s end the AAF program was virtually nonexistent in comparison with the more advanced Navy and Army Ordnance Department missile programs.” During the war, a group of scientists at the California Institute of Technology (Caltech) had been asked to study the V-1 and V-2 missiles. “[The]...scientists felt that rockets held great military promise and urged their development by the AAF Material Command [the Air Force]. But...[the] Materiel Command hesitated. The Army’s Ordnance Department, on the other hand, expressed a strong interest in rocket development.” By January 1944, the Ordnance Department of the Army was contracting with the California Institute of Technology (Caltech) to develop long-range surface-to-surface missiles.

23 Beard, pp. 22-23.
of each service to gain control of a new mission area. This is consistent with Clark’s point that military services can resist DOD directives.

The AAF campaign against the Army was moderated by fears that fights within the War Department (which contained the Army and the Air Force) over guided missiles might undermine AAF efforts to limit competition from the Navy Department (which contained the Navy and the Marines). Eventually the Army and the Navy saw themselves as natural allies against the Air Force’s attempt to monopolize missile development. If the Army cooperated with the Air Force against the Navy, they would eventually lose out to the Air Force as well. Better to call for equal opportunity for all services to pursue missile development. The Navy’s position was that it simply wanted to be able to continue its missile programs without fear that they would be transferred to some centralized program (presumably run by the Air Force).24

As stated above, this early controversy revolved around cruise missile systems, but ballistic missile research was also proceeding. During World War II, the U.S. Army captured 100 German V-2 rockets. As part of Operation Paperclip it brought the V-2’s, along with 130 of their developers, back to the United States for research and development.25 The U.S. Army Ordnance Department, seeing missiles as a natural extension of artillery, pursued the project. Their research team was headed by Doctor von Braun, the leader of the V-2 project in Germany.

In May 1946 at the White Sands Proving Ground, the Army’s Ordnance Department successfully fired their first V-2.26 It had required technical contributions from all three services to launch the rocket, but the Army received the publicity.27 General LeMay, head of Air Force R&D, was present at the launch of the first American

24Beard, pp. 32-33 & 40.
25Green, C. M. and Lomask, M., Vanguard: A History, Smithsonian Institution Press, City of Washington, 1971, p. 5, and Neufeld, p. 43. The British were actually collecting German rocket scientists before the American operation got going. Several scientists were “dragooned” out of the American-occupied zone. Fortunately for the U.S. many top scientists, including Von Braun, wanted to defect to the Americans because they felt that only America had the necessary resources for a large rocket project. And they were right. See Wulfsnt, Harry, The Rocketmakers Orion Books, New York, 1990, pp. 119-155
27Beard, pp. 34-36.
V-2. He had already developed a strategy to bypass the Army in the field of missiles. One month before the V-2 launch, the Air Force had contracted for studies of a missile that would deliver an atomic warhead between continents. LeMay felt that while the Army worked with smaller rockets, the Air Force would leap ahead with an ICBM.

Initially the Navy wanted nothing to do with the German scientists. By 1946 however, the Naval Research Lab (NRL) was developing the instrument packages for the V-2. Naval efforts were not limited to working with the Army. Both the Bureau of Aeronautics (BuAer) and the Bureau of Ordnance had missile projects of their own. The NRL got together with the Navy’s BuAer and proposed to work with the Air Force on rocket and satellite development. General LeMay turned them down, eventually producing an AAF-only proposal of his own. Apparently, General LeMay’s strategy was to see what the Army and the Navy were doing first, and then try to upstage them with an Air Force project. The Air Force began collecting German rocket scientists of its own.

Having been turned down by the Air Force, the Navy continued on its own. In 1946 the Navy Bureau of Ordnance and the NRL founded the Viking rocket program. Another BuAer effort for a joint satellite program was rebuffed by the Air Force in 1943. Faced with repeated rejection and a projected cost of $150 million, BuAer abandoned satellite research. Army Ordnance was put in charge of satellite R&D by the Technical Evaluation Group on Guided Missiles, chaired by Clark Millikan. But the committee also felt that satellites were not worth the cost, and Ordnance agreed with them. Satellite development would have to wait until the rockets were

28 Chapman, p. 28.
29 Wulforst, pp. 177 & 181.
30 Green & Lomask, pp. 5-6, and Neufeld, p. 43.
31 Neufeld, p. 36.
32 Green & Lomask, p. 7.
33 Wulforst, pp. 214-215. Walter Dornberger, Von Braun’s superior in Germany, persuaded the Air Force to free him from prison and a Nuremberg war crimes trial in order to work on rocket development for the Air Force.
34 Six were fired between 1946 and 1950. Some of these were launched from the National Advisory Committee for Aeronautics’ (NACA) Wallops Island test facility in Virginia. The Navy also launched a V-2 from the deck of the aircraft carrier Midway in September 1947. See McDougall, p. 99.
35 Hall, R. Cargill “Early U.S. Satellite Proposals” in The History of Rocket Technology edited by
available to launch them.

As with the Army, it seems that the Navy's impetus for missile research came from technically oriented agencies within the service. In the case of the Army, this was the Ordnance Department, which had engineered some impressive innovations in artillery. In the Navy's case, it was the NRL, the Bureau of Aeronautics, and the Bureau of Ordnance.

The Air Force was unimpressed with the V-2's accuracy. It was much more enthusiastic about the Snark, a cruise missile similar to the German V-1 that was to carry a 5000 lb. warhead between continents. The Air Force also had a bias towards air-breathing missiles with wings as opposed to the more alien V-2's, because the cruise missiles were seen as more practical.

The post-war service attitudes toward ballistic missiles can be summarized as follows. Technical branches within the Army and the Navy were making progress, but were hampered by lack of resources and sought alliances with other branches and other services to continue progress. The Air Force was behind, but whatever efforts it planned to make, it planned to make them alone.

The Air Force soon began to realize that long range missiles combined with atomic warheads represented a strategic bombardment capability. In a remarkably prescient memo, General LeMay wrote:

...The long-range future of the AAF lies in the field of guided missiles. Atomic propulsion may not be usable in manned aircraft in the near future, nor can accurate placement of atomic warheads be done without sacrifice of the crews. In acceleration, temperature, endurance, multiplicity of functions, courage, and many other pilot requirements, we are reaching human limits. Machines have greater endurance, will stand more severe ambient conditions, will perform more functions accurately, will dive into targets without hesitation. The AAF must go to guided missiles for the

Eugene M. Emme, Wayne State University Press, Detroit, 1964, pp. 85-86.

McDougall, p. 89.

initial heavy casualty phases of future wars.\textsuperscript{38} [Emphasis in original]

It was the mission of strategic bombardment that the Air Force felt it must retain, above all others. The Air Force had just recently become independent. Its independence and future growth was founded on the principle of long range strategic bombardment by aircraft. Anything that could possibly compete with long range strategic bombers had to be controlled by the Air Force—including ballistic missiles. To this end, the Air Force offered the Navy a deal whereby, if the Navy would agree to develop only short range missiles designed to support traditional Navy roles, the Air Force would not threaten these projects. But the deal was never struck.\textsuperscript{39}

It was the Army’s Ordnance Department and the Navy’s NRL that took the initiative in rocket development. The Air Force, on the other hand, appears to have only become seriously interested in missiles after one of its core missions, strategic bombardment, was potentially threatened. The Air Force tended to respond to the moves of others, rather than taking the initiative itself.

The AAF argued that it should get exclusive control of all missile development. In April 1946, the Army sided with the Navy against the Air Force in calling for a national program with joint procurement, testing, and training. In October 1946, the Secretary of War (Air) assigned responsibility for all Army guided missile Research and Development (R&D) projects to the AAF.\textsuperscript{40} Again, Army Ordnance joined with the Navy to resist this assignment.\textsuperscript{41}

The July 1947 National Security Act created the Air Force as a separate service. A set of agreements between the Army and the Air Force stated that the Air Force would work on strategic missiles, while the Army would work on tactical ones. This was a definite victory for the Army in reversing the 1946 assignment. Further, the directive did not specifically define “strategic” and “tactical,” which left the Army considerable latitude.\textsuperscript{42}

\textsuperscript{38}Memo fro LeMay to Spaatz, 20 September 1946, quoted in Beard, p. 39.
\textsuperscript{39}Beard, p. 41.
\textsuperscript{40}However, no personnel, funds, or contracts were to be transferred as a result of this directive until a plan could be developed.
\textsuperscript{41}McDougall, pp. 23, 51, & 90.
\textsuperscript{42}Beard, pp. 43-44.
However, the entire inter-service struggle was put on hold when funding for all missile programs was drastically cut after 1946. The dispute would remain frozen until significant funding was restored.\(^{43}\)

### 10.2.2 Decline in Missile R\&D: The Late 1940's

By 1947, the race to develop long range missiles was about to be reduced to a crawl. Civilian skepticism and Eisenhower Administration economy measures had drastically reduced budgets and virtually halted development efforts. Dr. Vannevar Bush, head of the Joint Research and Development Board (JDRB),\(^{44}\) had serious doubts about the feasibility of long range rockets.\(^{45}\) Before Congress he stated “In my opinion such a thing is impossible and will be impossible for many years.”\(^{46}\)

The JRDB was composed of two Army, two Navy, and three civilian representatives. They avoided controversy and sought compromise. Consequently, they were unable to resolve inter-service disputes. It was the Eisenhower administration’s economy directives that prevented any service from receiving significant rocket or satellite research funding.\(^{47}\)

Through 1946, things had gone well for the Air Force. It had a contract with Convair to build the first ICBM.\(^{48}\) If built, this was a system that would be capable of putting objects into space. After Fiscal Year 1946 (FY46), rocket development funding rapidly declined. The funding history for missile development during the late

---

\(^{43}\) McDougall, pp. 91 & 98-99.

\(^{44}\) In August 1946, all guided missile research coordination was shifted to the JDRB, which later became the Defense Research and Development Board (RDB). See Beard, p. 74.


\(^{46}\) Bush, Vannevar. Hearings, Inquire into Satellite and Missile Programs, pp. 822-23. Quoted in Beard, p. 70. The rest of the quote is: “The people who have been writing these things that annoy me have been talking about a 3,000-mile high-angle rocket shot from one continent to another carrying an atomic bomb, and so directed as to be a precise weapon which would land on a certain target such as this city. I say technically I don’t think anybody in the world knows how to do such a thing, and I feel confident it will not be done for a very long period of time to come. I think we can leave that out of our thinking. I wish the American public would leave that out of their thinking.”

\(^{47}\) Hall, pp. 51-52, 83.

\(^{48}\) The contract was with the Vultee Aircraft Corporation (later known as Convair) for $1.4 million to develop a 5,000 mile range surface-to-surface missile with a 5000 lb. payload and a Circular Error Probable (CEP) of 5000 ft. (See Beard, p. 50 and Neufeld, p. 45). Circular Error Probable is the radius within which one can statistically expect half of the missiles to land.
40’s and 50’s is shown in Table 10.1.\footnote{By December 1946, the 26 Air Force missile projects had been cut to 17 projects, 11 by spring 1947, 8 by summer 1948, and 4 by June 1950 (See Beard, pp. 53 & 89). Funding was so tight that the Air Force actually transferred one air-to-underwater missile project to the Navy rather than see it die (See Neufeld, pp. 27 & 42).}

The Convair ICBM contract was one of the first projects to go. Leftover money was used to launch three prototypes tests in 1948, all three launches failed.\footnote{Neufeld, p. 50} In 1949 the Air Force did try to get funding for the rocket as a high-altitude research vehicle, but the Navy’s Viking rocket was already performing this role. The Navy was able to convince the JDRB to cancel the ICBM project a second time in February 1949.\footnote{Beard, pp. 63-67 & 131.} During 1949 and 1950 Convair funded the rocket project on its own at a cost of $3 million.\footnote{Chapman, p. 50.} The Air Force continued to fund guidance studies.\footnote{Chapman, p. 56.}

Although it had struggled to get control of all missile R&D, and although it had tried to fund the Convair project, the Air Force was not enthusiastic about ballistic missiles. “Within the Air Force itself, some diehard fliers were wondering what the air branch was doing in the missile game in the first place. They contended that air vehicles without cockpits didn’t belong in the Air Force.”\footnote{Chapman, p. 131.} In 1949 the Air Force listed it’s guided missile priorities. These were: first, bomber-launched air-to-surface and air-to-air missiles; second, air defense surface-to-air and fighter-launched air-to-air missiles; and third, surface-to-surface missiles.\footnote{Beard, pp. 84-85.} The bias was toward support of aircraft operations, not replacement. To be fair, ballistic missiles were still an unproven technology. The Air Force view was that “guided missiles … were clearly not so important. Their effectiveness, indeed their feasibility, as very long range bombardment weapons was not certain. Their expense, on the other hand, was very obvious and provided adequate reason for a slow, cautious approach.”\footnote{Beard, p. 77.} The Air Force view was twofold: first, ballistic missiles were a threat to the long range bombers and must be under Air Force control; and second, ballistic missiles were impractical and
<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>IRBM &amp; ICBM Programs</th>
<th>Other Surface-to-Surface Missile Programs</th>
<th>All Other Missile Programs</th>
<th>Grand Total All Missile Programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1946 &amp; Prior</td>
<td>2.0</td>
<td>19</td>
<td>51</td>
<td>72</td>
</tr>
<tr>
<td>1947</td>
<td>—</td>
<td>20</td>
<td>38</td>
<td>58</td>
</tr>
<tr>
<td>1948</td>
<td>0.3</td>
<td>36</td>
<td>45</td>
<td>81</td>
</tr>
<tr>
<td>1949</td>
<td>0.1</td>
<td>45</td>
<td>53</td>
<td>98</td>
</tr>
<tr>
<td>1950</td>
<td>—</td>
<td>65</td>
<td>69</td>
<td>134</td>
</tr>
<tr>
<td>1951</td>
<td>0.5</td>
<td>185</td>
<td>598</td>
<td>784</td>
</tr>
<tr>
<td>1952</td>
<td>0.8</td>
<td>239</td>
<td>818</td>
<td>1,058</td>
</tr>
<tr>
<td>1953</td>
<td>3.0</td>
<td>403</td>
<td>760</td>
<td>1,166</td>
</tr>
<tr>
<td>1954</td>
<td>14</td>
<td>336</td>
<td>717</td>
<td>1,067</td>
</tr>
<tr>
<td>1955</td>
<td>159</td>
<td>398</td>
<td>911</td>
<td>1,468</td>
</tr>
<tr>
<td>1956</td>
<td>526</td>
<td>387</td>
<td>1,368</td>
<td>2,281</td>
</tr>
<tr>
<td>1957</td>
<td>1,401</td>
<td>603</td>
<td>2,502</td>
<td>4,506</td>
</tr>
<tr>
<td>1958</td>
<td>2,150</td>
<td>639</td>
<td>2,391</td>
<td>5,180</td>
</tr>
<tr>
<td>1959</td>
<td>2,946</td>
<td>685</td>
<td>3,269</td>
<td>6,900</td>
</tr>
</tbody>
</table>

Table 10.1: Defense Obligational Program for Missile Systems Fiscal Years 1946-60 (in millions of dollars).

Source: Chart found in U.S. Congress, Senate, Committee on Armed Services, Preparedness Investigation Subcommittee, *Hearings: Missiles, Space, and Other Major Defense Matters*, 86th Congress, 2nd Session, 1960, p. 509. Quoted from: Beard, Edmund. *Developing the ICBM* A Study in Bureaucratic Politics, Columbia University Press, New York, 1976, p. 206. Explanation included: “Program data reflected in this table over the development and capital costs involved in missile programs, i.e., the cost of bringing missile systems to operational status plus the costs of procuring missiles and related equipment for operational purposes. These data include all procurement, construction and research and development programs directly associated with missile programs. These figures do not include military pay, operation and maintenance costs for operational missile units and sites, and include only those shipbuilding and aircraft costs directly associated with providing missile capability.”

296
need not be seriously pursued.\textsuperscript{57}

Given the threat to strategic bombers, the Air Force effort to obtain a monopoly on all rocket research makes perfect sense. What also makes perfect sense is the Air Force's "go slow" attitude toward missile development. In the early days,\textsuperscript{58} when the Air Force was struggling for its independence, aircraft represented autonomy and a new way of waging war. By the late 1940's, having achieved this new role of strategic bombing, it also developed a new conservatism. It now had a clear mission (strategic bombardment of the Soviet Union) which was driving the procurement of a lot of advanced, expensive, long range aircraft. Protecting this mission became more important than exploring new ways to deliver bombs. Building manned aircraft became more important than exploring the latest technologies of unmanned flight. The Air Force was creating a bomber fleet and considered this to be the best means of providing national security. The Air Force was not open minded about alternative means of strategic bombardment. This is the "goal displacement" Lucas and Dawson talk about.\textsuperscript{59} The Air Force was selective in the types of technology it wanted to pursue. The manned strategic bomber was a winning system: it provided for more funding and growth. Projects that enhanced the manned bomber, and secondarily the manned fighter interceptor, were pushed.

Meanwhile, the Army's von Braun team, having won approval to work only on tactical missiles, with little funding, continued to launch the captured V-2's until they ran out. In 1950 the team moved to the Ordnance Guided Missile Center at Redstone Arsenal, in Huntsville Alabama.\textsuperscript{60} They began building the Redstone rocket, which would fly in August 1953.\textsuperscript{61} The project was initiated as a "short range ballistic rocket"\textsuperscript{62} but was in fact the first large U.S. booster to be produced. The Redstone rocket would launch the first U.S. satellite into orbit and the first American into

\textsuperscript{57}Beard, p. 90.
\textsuperscript{58}The Army Air Corps was established in July, 1926. Neufeld, p. 9.
\textsuperscript{59}Lucas and Dawson, p. 13.
\textsuperscript{60}York, p. 82.
\textsuperscript{61}McDougall, pp. 99.
\textsuperscript{62}Beard, p. 104
Summarizing the 1940's, we see that the Germans demonstrated that guided missiles might be the weapon of the future. Parallel efforts were begun in all three services, with the Army and the Navy taking the lead. Repeated civilian efforts to assign missile responsibilities failed. The Army and the Navy allied to keep the Air Force from controlling all missile development. Navy efforts toward joint satellite development failed. The Air Force made its own proposal rather than cooperating, and the Army ignored satellites. The Army had the strongest rocket program (the Von Braun team and the captured V-2's), followed by the more modest Navy program (the Viking). The Air Force's program was the most ambitious (a true ICBM), but failed to get sufficient funding. Instead the Air Force pushed cruise missile development.

10.2.3 Missile Development: the 1950's

During the 1950's, missiles attracted new converts, both civilian and military. A pro-missile group had formed within the Air Force, but it was unable to affect Air Force R&D funding decisions until civilian intervention forced changes. The Army and Navy continued to pursue their projects but eventually lost out to the Air Force's more ambitious and better funded efforts. The Army dropped out of the booster competition while the Navy retired with a piece of the strategic bombardment mission: the Submarine Launched Ballistic Missile (SLBM).

During this decade, the U.S. built the rockets that would take the U.S. military into space. All of the boosters used by the U.S. military today (with the exception of the Space Shuttle and Scout sounding rocket) are incrementally improved versions of the Air Force rockets built in the 1950's.\(^\text{64}\)

After five lean years, long range missile funding was restored in 1951. The Russian atomic bomb test (August 1949) and the beginning of the Korean war (July 1950) jolted the economy-minded civilians and took rocket development off the back burner.


In 1951 the Air Force ICBM project (now called Atlas) was again funded, but for the next four years the funding was minimal. Ballistic missile enthusiasts within the Air Force wanted $4.5 million to proceed with development, but were overridden by more conservative elements within the Air Force. The cruise missiles (such as the Snark and Navaho) continued to absorb the vast majority of R&D funds. As Table 10.1 shows, Fiscal Year 1952 funding was only $0.8 million for long-range missiles, while other missile programs were commanding hundreds of millions of dollars. The cruise missiles were obsolete by the time they become operational. Some were obsolete before they became operational. But not all the money spent on these programs was wasted. The engine developed for the Navaho was used in a modified form as the basis for the Army's Redstone rocket, and the Air Force's Atlas rocket. The contractor which built the Navaho engine, Rockedyne, continued the engine series to produce engines for the Thor, Jupiter, and Saturn rockets. While building an entire cruise missile is not the most efficient way to get a new engine design, the cruise missile projects did contribute to rocket projects to follow.

One argument used by the Air Force to limit ICBM development was that a ballistic missile would be unable to carry large, heavy atomic weapons. The Air Force had set the accuracy and weight requirements so high that ballistic missiles would be unable to attain them any time soon. By December 1950, Convair's requirements were to deliver an 8000 lb. warhead 5,000 nautical miles, with a 1500 ft. accuracy. The requirements were very unrealistic. For example, the payload requirements were derived from the early atomic bombs. But new, lighter atomic warheads had been successfully tested in 1949. Beard argues that the requirements were simply a device for keeping ballistic missile development where the pro-bomber group wanted it: in

---

65 Chapman, p. 61. The Air Force issued the contract to Convair in January 1951 for $0.5 million to study both ballistic missiles and a combination ballistic/cruise type of missile. See Beard, p. 132.
66 York, pp. 80-81.
69 York, p. 81.
70 Neufeld, p. 65.
71 Beard, p. 141.
the far future. The Air Force issued unrealistic requirements for its bombers as well as its missiles. Unrealistic requirements were a normal part of Air Force contracting. But the bombers were funded while the ICBM was not. While ambitious Air Force requirements seem to have supported aircraft development, they impeded missile development.

The Army's interest in rockets rivaled that of the Air Force. The Army's early enthusiasm is consistent with Clark's theory that a service that views itself as losing the funding competition will be innovative. Post-World War II military funding was shifted toward the Air Force's strategic bomber program, away from the Navy and especially from the Army. Strategic missiles represented a potential new mission area for the Army.

The Air Force had won the post-war competition for funds. As Clark predicts, it was not terribly interested in developing new systems, like rockets. Instead the Air Force concentrated on improving existing systems, like bombers. It was the losers of the funding war who were innovative: the Army and the Navy. But when a core mission was threatened by these innovations, then the Air Force attempted to take over this new means of delivery. This is consistent with Thompson's idea that an organization will seek to control areas that affect its central mission.

Just as Atlas was a potential threat to the bomber program, it was also a threat to the cruise missile programs (Navaho and Snark). The cruise missile consumed much more money than the ballistic missiles. Here again we see the bias toward cruise missiles as well as unrealistic requirements being used to forestall development of the Atlas.

In December 1952, an ad hoc committee chaired by Dr. Clark B. Millikan was set

---

72 For a good description of Air Force bomber contracting behavior and the problems that it created, see Brown, Michael E. Flying Blind: the Politics of the U.S. Strategic Bomber Program Cornell University Press, 1992.


74 Some in the Air Force also believed that the JDRB committee on Guided Missiles would be hostile, questioning the Atlas's ability to attain the 1,500 ft. CEP requirement. See Neufeld, p. 71. They also feared that the JDRB would question the Air Force's ability to fund Atlas, Navaho, and Snark simultaneously.
up by the Air Force Scientific Advisory Board. It recommended the requirements be relaxed to a 3000 lb. payload, a one mile CEP, and a 5,500 na-mi. range.\textsuperscript{75} The Air Force resisted the CEP increase, just as it resisted lowering any of its requirements for any of its bombers. The new requirements were to send a 3000 lb. warhead, 5,500 na-mi. with a 1500 ft. accuracy. In March 1954, the required CEP was finally relaxed to 2 to 3 na-mi.\textsuperscript{76}

The Atlas program gained an important ally when a new special assistant for R&D, Trevor Gardner, was appointed under the Eisenhower administration in 1953. Gardner exhibited the personality traits one sees in so many military innovators.\textsuperscript{77} He sided with those who believed in moving missiles to the development stage quickly. But despite his enthusiasm, the Air Staff directed the Air R&D Command to take a slow approach toward ballistic missiles. And in March 1953, efforts to expand the Atlas program were again turned down by Air Force Headquarters.\textsuperscript{78}

Gardner decided that he needed a vehicle to promote his cause.\textsuperscript{79} He formed the Strategic Missile Evaluation Committee or “Teapot Committee” chaired by John Von Neuman. In February 1954, the committee concluded that the Atlas program requirements were still too strict and that the program was under funded. Gardner used this report as the basis for his recommendations.\textsuperscript{80} Here, another aspect of Air Force policy came into play: fear that the missile project would be taken away from them. This fear spurred them to action. As Beard states:

Once again the dual nature of the Air Force response to long-range missiles became evident. On the one hand, the Air Force had consistently underrated their effectiveness and even their feasibility. Manned aircraft were continually promoted over the missile competitors on the grounds

\textsuperscript{75}The 5,500 na-mi. range was a “round number” equal to exactly one quarter of the Earth’s circumference and a typical U.S. to U.S.S.R. distance. See York, p. 89.
\textsuperscript{76}Neufeld, pp. 74 & 102
\textsuperscript{77}“Trevor Gardner was a ‘sparkplug,’ an active individual who did ‘a tremendous job in expediting the development of the missile, in directing funds and brainpower into the missile program.’ Also described as ‘sharp, abrupt, irascible, cold, unpleasant, and a bastard...’ ” See Neufeld, p. 96.
\textsuperscript{78}Beard, pp. 145-150.
\textsuperscript{79}Perry, p. 144, Chapman, pp. 72-74, and Wulforst, p. 219.
\textsuperscript{80}Beard, p. 162.
of cost, trustworthiness, efficiency, and capability. On the other hand, missiles were generally admitted to be a potentially useful weapon for the future—but a future placed far enough ahead to be meaningless.

Nevertheless, long-range missiles were considered to be an Air Force weapon and an Air Force responsibility. This possessiveness had been demonstrated many times in territorial battles with the Army and Navy. In each case the Air Force’s responsibility for the strategic function in American defense planning was stressed and with that functional responsibility came all weapons capable of fulfilling it. Long-range missiles might not be emphasized by the Air Force; but no one else was going to build them either, if the Air Force could help it. 81

The fear of losing the project caused the Air Force to accept changes to speed progress on the Atlas project. Gardner created a separate organization within the Air Force, the Western Development Division (WDD), in February of 195482 and it was given highest priority.83 A pro-missile colonel, Bernard Schriever, was rapidly promoted and put in charge of the project by Gardner.84 Looking back at Table 10.1 (p. 296), we see that from this point onward, missile funding increased substantially.

In 1955, Schriever and Gardner persuaded Congress and the President to issue a directive giving them more contracting authority. The normal chain of command through the Air Force was bypassed. In effect, “An entirely new agency had been created specifically to manage the ballistic missile program.”85

This demonstrates the enormous power civilians have to bypass service priorities. The missile advocates within the Air Force were gradually given the money and an organization to build missiles, independent of the existing Air Force organization. In

81Beard, p. 167.
82Neufeld, p. 94.
83In June 1957 it would become the Air Force Ballistic Missile Division (BMD). See Neufeld, p. 167.
84Schriever was a member of the pro-missile minority within the Air Force and had been a promoted to Brigadier General from Colonel only nine months before the WDD was founded (See Wulforst, pp. 219-220, and Chapman, p. 71.) By October 1955, Schriever was a Major General (See Neufeld, pp. 3 & 140).
85Beard, p. 194.
the end, the Strategic Air Command (SAC) received operational responsibility for ICBMs, but the missiles were built largely outside the traditional Air Force. And SAC did not intend to give ICBMs a starring role in its inventory. General LeMay was now head of SAC, not Air Force R&D. Despite his earlier visions of the future, LeMay's view of the current role of ICBMs was quite limited. 86 "LeMay believed that the military worth of ICBMs lay in their 'political and psychological value,' but in no case would ICBMs alone 'be capable of destroying the target system.' 87

Certainly the Atlas presented problems as an ICBM. It was slow to fuel and fire, and vulnerable while on the ground. Structurally, the Atlas was fragile: without pressure in its fuel tanks it couldn't stand upright or support its payload. The Atlas was literally a stainless steel balloon. 88 One solution to these problems was the two-stage Titan ICBM, which used many Atlas components, 89 begun in May 1955. The Titan had a stronger structure and Titan II used storable hypergolic fuels. The final solution was the three-stage Minuteman, 90 which used solid fuel (something the Air Force learned from the Navy, see below) and could be fired with 60 seconds warning. The Minuteman project began in 1956. 91 By the mid 1950's the Air Force had become the undisputed owner of the land-based ICBM, but the other services remained active in the development of booster technologies.

The Navy's IRBM

In 1955, as part of a general increase in missile activity, the Army and the Navy created missile-building sub-organizations: the Army Ballistic Missile Agency (ABMA), and the Special Projects Office (SPO). 92 In 1955, the Special Projects Office joined with ABMA, headed by General Medaris, to work on the Army's Jupiter IRBM, a liquid fueled derivative of the Redstone rocket. Like the WDD in the Air Force and

---

86 York, p. 53.
87 Neufeld, p. 142.
88 York, p. 96.
89 Neufeld, p.123.
90 York, p. 97.
91 McDougall, pp. 128-129.
92 McDougall, pp. 128-129.
the SPO in the Navy, ABMA was a highly autonomous and independent organization within the Army that specialized in missile development.\footnote{Medaris, pp. 71-72.}

The joint IRBM project proved to be simply a maneuver on the Navy's part, designed to get them into the rocket development business.\footnote{Eisenhower limited the number of missile projects to four. Three were Air Force (Atlas, Thor, and Titan) and one was Army (Jupiter). The Navy was told that it would not be allowed to start a new missile project and that it would have to join an existing project. So it joined with the Army which was looking for reasons to justify the Jupiter project. The Navy immediately initiated studies of solid fueled rockets. See Sapolsky, Harvey M., \textit{The Polaris System Development} Bureaucratic and Programmatic Success in Government, Harvard University Press, Cambridge, Massachusetts, 1972, pp. 7-8 and Armacost, pp. 93 & 104.} As soon as it became possible (July 1956), the Navy pulled out of the project and began developing a solid fueled rocket.\footnote{McDougall, p. 129.} This was the Polaris, a submarine-launched ballistic missile.

The Navy had needed the Army joint project to get into the rocket field. The sea-based version of the Jupiter missile gave the Army an importance justification for its project, so it welcomed the Navy and made substantial modifications to the Jupiter design for shipboard use. Later, the Navy needed Air Force to support to get a separate missile project. It voted with the Air Force in the JCS to strip the Army of operational control of land-based missiles in October 1956.\footnote{Sapolsky, p. 33 and Armacost pp. 55, 104-110, 118.} In other words, the Navy was able to exploit the competition between Army and the Air Force to its own advantage by siding with the Army and then the Air Force.

Solid fuel research had been conducted by both the Army and the Air Force\footnote{Neufeld, pp. 40, 42, 122, 147, 182 and Armacost, p. 59.} but Polaris was the first large missile project to use solid fuel. Solid fuel lessened the problems of storing missiles at sea aboard submarines. The Navy had been very clever in building a solid fueled rocket that could perform its mission only if a light weight atomic warhead were available. Based on existing work, the Navy looked at trends in atomic warhead design and anticipated that such a warhead would be available by the time the Polaris was ready to fly. And it was right. Polaris gave the Navy a unique capability: sub-based missiles, which were invulnerable to surprise attack.

The Special Projects Office was able to develop a strong organizational \textit{esprit de}
corps while at the same time accommodating forces within the Navy and obtaining support from scientists. A new managerial system (called PERT) was used as a shield to fend off inquiring civilian officials. Outsiders became involved in the wonders of PERT, letting the office perform its tasks unhindered. “PERT did not build the Polaris, but is was extremely useful for those who did build the weapon system to have many people believe that it did.”

There were some similarities between the WDD and SPO. Both were special purpose organizations carved out of the service to produce ballistic missiles. Both were needed to provide a separate funding channel because of service resistance. But there also were marked differences between the Air Force and the Navy in their approach to missile development. Once the Navy’s SPO got the authority to produce the Polaris, it devoted considerable effort to keep civilians from interfering with their project. The Navy missile builders considered it a requirement to keep the civilians from intervention.

In contrast, the Air Force missile builders had required civilian intervention to create the WDD, to fund missile production, and to lower requirements. Further, successive interventions were required to give the WDD the necessary autonomy to perform its assignment.

Like the Air Force’s WDD, the Navy’s SPO was also set up for political reasons, but they were somewhat different reasons. The submariners were not happy with this new mission and would rather accept fewer boats than abandon their attack role. Fortunately, Polaris had some backing at the top of the Navy hierarchy, namely Arleigh Burke the Chief of Naval Operations. Navy officers feared that Polaris funds would come at the expense of other Navy projects. The SPO was created for two reasons. First, it preempted any competition between the Bureau of Astronautics

---

99Sapolsky, p. 125.
100“Attack boats” are used to attack ships and other submarines at sea. They seek out targets and destroy them. Polaris boats (and their descendants) specialize in hiding from others. Submariners at the time considered this a much less glamorous mission.
101Sapolsky, pp. 18, 21, & 23. The officers were right. Sapolsky demonstrates that Polaris funds did come at the expense of other Navy projects.
and the Bureau of Ordnance over which bureau would get the project. Second, the civilian leadership promised that the SPO would be funded outside normal Navy appropriations.

Air Force payload requirements were set high, based on existing bomb weights, which retarded missile development. On the other hand, the Navy was basing its requirements on weapons that had not yet been developed in order to expedite the process, and it was innovative in the use of solid fuel. Both services used weight requirements for political ends, but opposite political ends. Again we find confirmation of Clark’s theory that the service that views itself as the budgetary loser in a competition for funds will be aggressive and innovative in research and development. Although the Navy’s budget was higher than the Army’s, it’s budget was substantially less than the Air Force’s throughout the 1950’s because the Air Force had a monopoly on strategic bombardment. Polaris was the Navy’s entry into that mission area.

These differences between the Air Force and the Navy approaches to missile development are understandable given their organizational incentives. The Air Force was slow to move forward with ICBMs because missiles might have threatened the strongest group within the Air Force: the bomber pilots. In developing ICBM’s, the Air Force was primarily motivated by the fear of other services getting the missile mission, first the Army and then later the Navy. Competition made the Air Force fearful of losing its dominance in ballistic missiles.

This situation was exactly reversed within the Navy. Competition made the Navy ambitious to develop a ballistic missile role. The Polaris project represented an addition to the Navy’s existing mission, a potential area for expansion. That area was strategic bombardment, the mission that had allowed the Air Force to become the dominant service.

With the new solid fueled Polaris, the Navy was able to capture a unique part of the strategic bombardment, the invulnerable second strike capability, one that it retains to this day.\textsuperscript{102} The Air Force later challenged the Navy’s role, but the Air

\textsuperscript{102}In fact, today the submarine ballistic missile force is emerging as the core of the U.S. nuclear
Force failed to either cancel or take control of submarine-based ballistic missiles. Once the Army’s Jupiter had been dispatched, the Air Force attacked the Polaris program. In his memoirs, General Curtis LeMay points out that submarine-based missiles are more expensive to build and maintain that ground-base ones. He claims that multiple basing systems are good, but that “...we went overboard on the Polaris.”

The Air Force noted Polaris’s low yield warhead and criticized the initial plan to keep only 25% of the submarine force on-station at any given time. In response, the Navy developed the dual-crew system to get the on-station rate up to 50%. The Navy was quite sensitive to the Air Force’s desire to either kill or control the Polaris program. As Sapolsky puts it:

Polaris partisans saw the Air Force threat everywhere. The frequent visits of retired Air Corps generals to their wartime friend in the White House were viewed as an Air Force device to pass on pro-Minuteman (and anti-Polaris) arguments directly to President Eisenhower. Reporters who had made the rounds of Air Force installations always appeared to have extremely distorted opinions about the FBM [Fleet Ballistic Missile] system’s invulnerability and technical capabilities. Admiral Raborn at one point asked General Schriever, the commanding officer of the Air Force Ballistic Missile Division, to intervene with the people at the Wright Field Air Force Laboratories who were said to be spreading misinformation about the Polaris guidance equipment. And, of course, the Air Force strongly argued that the operational FBM system be combined with the other strategic missiles and placed under the direct control of the Air Force’s Strategic Air Command.

When the time came, the Navy attacked the Air Force’s Minuteman program. In 1958 it promoted the Polaris as a solid fueled ICBM which was available now. The

---

104 Sapolsky, pp. 39-41.
105 Sapolsky, p. 40.
Navy predicted that the Minuteman wouldn’t be available until 1965. It also claimed that the Minuteman would be vulnerable to pinpoint attack. In response, the Air Force initiated action to put missiles in railroad cars. After securing approval for the Minuteman, rail basing became a secondary priority. Minutemen were never deployed in rail cars, but it is interesting to note that the idea of a rail-based ICBM is not new.

Summarizing the Polaris history, we see that the Navy wanted a piece of the strategic bombardment mission and was willing to be flexible and to take the initiative to get it. In contrast to the Air Force, the Navy anticipated nuclear weapons designs in determining it missile requirements, and pioneered the use of solid fuels. The Navy encountered internal resistance, but unlike the Air Force, the Navy had no strategic bomber program that might be threatened by missile development.

The First U.S. Satellite

Competition between the services intensified in July 1955 when the White House announced that it would launch a satellite as part of the International Geophysical Year to begin in July 1957. Each service had its own proposal: the Army offered a derivative of it’s Redstone rocket (also known as the Jupiter-C); the Naval Research Laboratory put up it’s Viking rocket under the title Project Vanguard; and the Air Force proposed using it’s Atlas rocket.

The administration went with Vanguard. This was the only proposal that did not involve a group working on an ICBM or IRBM. The Eisenhower administration wanted to keep U.S. space activities on a civilian footing until reconnaissance satellites were accepted internationally. Also, the administration did not want to disrupt existing work on missiles in order to launch a satellite.

---

106Neufeld, pp. 229-230.
107The Navy was not the first to use solid fuels. Both the Army and the Air Force did development work in solid fuels (see Neufeld, pp. 40 & 42). The Air Force’s WDD began a serious solid fuel research effort at the end of 1955 (see Neufeld, pp. 122 & 147). But the Navy was the first to use it in a major rocket development effort.
108The rocket was called a Jupiter-C to identify it with the Army’s Jupiter IRBM project. See Medaris.
109Stares, p. 34.
But the services recognized the prestige associated with “firsts” in space, even if Eisenhower did not. The missile programs were disrupted by the satellite effort, especially in the Army. The Army tried to get the satellite mission transferred from the Navy to the Army during the Summer and Fall of 1956, but failed.\footnote{Armacost, p. 115.} “We at Huntsville could not scrap the satellite idea, and we did not scrap our satellite-oriented hardware.”\footnote{Von Braun, p. 111.} A September 1956 Jupiter-C launch could have gone into orbit, but the Army was explicitly prohibited from doing so. When the Soviet Sputnik was launched, the Army began preparations for a satellite launch, anticipating permission from the Eisenhower Administration.\footnote{Medaris, pp. 119-120 & 165-186.} With Sputnik, the space race began. Sputnik created a panic that the U.S. was falling behind the Soviet Union in rocket technology. The pressure on Eisenhower to do something was tremendous.

The first Vanguard failed one second after launch and blew up on the pad in December of 1957.\footnote{Green & Lomask, p. 283.} By then the administration had turned to the Army’s Redstone rocket,\footnote{Redstone rockets were being used to test Jupiter components. After Sputnik, Medaris began preparations to launch a satellite on the assumption that the administration would turn to the Army. See Medaris, pp. 119-120 & 165-186.} which successfully launched the first U.S. satellite in January 1958. Vanguard eventually succeeded,\footnote{With another launch failure, Vanguard launched a 4 pound satellite into orbit in March 1958. This was followed four more failures, but finally a 24 lb. satellite was launched in February 1959. See Green & Lomask pp. 283-285.} but from this point on the Navy was out of the booster business. It would go on to develop new SLBM’s and military satellites, but Navy rockets would never again carry men or machines into space. By the end of the 1950’s, the booster competition had narrowed to two: the Army and the Air Force.

The Air Force also wanted to launch a satellite, but was told not to do so until Atlas had flown the required 5,500 na-mi. range.\footnote{Chapman, p. 153.} The Air Force arrived late to the satellite competition, but out-performed the other U.S. systems. It launched an entire Atlas missile (minus the fuel and two engines) weighing 1,412 lb. into orbit in December of 1958.
The IRBM Struggle

After the Navy's move to the solid fueled Polaris, the Army was left to go it alone with the Jupiter. In the fall of 1955, the Air Force began development of its own IRBM, the Thor, in response to the Army IRBM program.\textsuperscript{117} When it was suggested that the Army could develop the IRBM for the Air Force, General Schriever said, "It would be naive to think that the Army would develop a weapon and then turn it over to the Air Force to operate. Therefore, I strongly recommend that our relationship with Redstone remain on an exchange of information basis."\textsuperscript{118} In fact, the Army did develop the Jupiter IRBM, only to turn it over to the Air Force to man and deploy. But by then the Thor was also being manned and deployed.

Both projects ran in parallel, with the Department of Defense (DOD) turning a blind eye to the duplication. Jupiter began testing in September 1956, Thor in January 1957.\textsuperscript{119} As one historian wrote:

The missile competition, particularly between the Army and Air Force, became an intense and heated rivalry, which gradually grew bitter. By 1955 the competition spilled over into the public eye. The Air Force and Army exchanged accusations that year before congressional hearings on the state of America's missile development. General Medaris publicly accused top Air Force Brass, and General Schriever specifically, of attempting to conceal and withhold valuable technological data from the Army by delays, bureaucratic obstruction, and outright refusal to share information.\textsuperscript{120}

In October 1955, the Joint Chiefs of Staff (JCS) were ordered to consider the IRBM programs. Initially split, they eventually compromised on having two IRBM programs.\textsuperscript{121} In other words, neither the Army nor the Air Force was willing to give

\textsuperscript{117}Armacost, p. 62.
\textsuperscript{118}Neufeld, p. 144.
\textsuperscript{119}McDougall, p. 129.
\textsuperscript{121}Neufeld, p. 146.
up its system.

Secretary of Defense Charles E. Wilson tried to eliminate the Jupiter in November 1956. He was blocked by General Medaris and Von Braun, but as a result of the struggle, the Air Force got the IRBM mission.\textsuperscript{122} It was assigned operational responsibility for all IRBMs, including the Army's Jupiter. Further, Secretary of Defense Wilson limited the Army to missiles of ranges 200 miles or less.\textsuperscript{123}

The Air Force continued to develop the Thor and continued to try to kill the Jupiter. In August 1957, all IRBM work was temporarily halted, pending a study that would pick one missile for the role of IRBM. The study couldn't decide, suggesting instead the continued development of both until one emerged as clearly superior. The launch of Sputnik, in October if 1957, got both programs moving again.\textsuperscript{124}

In April 1958, Secretary of the Air Force Douglas attempted, once again, to kill the Jupiter. Again he was blocked by the JCS.\textsuperscript{125} What is surprising here is not that the Air Force tried to kill the Army missile, but that the Army defended it so tenaciously at the JCS level. From 1956 onward, the IRBM, regardless of manufacturer, was destined to fall into Air Force hands. Yet the Army continued to develop and to fight for its program, and tried to get the first satellite mission, to prove that Jupiter was superior to the Air Force's missile.\textsuperscript{126} Perhaps it felt that if the Jupiter proved far superior to the Thor then the mission allocations would be changed, just as the first U.S. satellite decision was changed when the Jupiter proved superior to Vanguard.

Now a flood of systems became operational. The IRBM's began deployment in Europe in June 1959. The Thors went to England, the Jupiters went to Italy and Turkey. The first Atlas became operational in August 1960\textsuperscript{127} and the first Polaris boat became operational in November 1960.\textsuperscript{128} The Titan was deployed in April 1962, and the Minuteman in October 1962.\textsuperscript{129}

\textsuperscript{122} York, p. 101.
\textsuperscript{123} Neufeld, pp. 150 & 163.
\textsuperscript{124} Beard, p. 186, and Neufeld, p. 169.
\textsuperscript{125} Neufeld, p. 223.
\textsuperscript{126} Neufeld, p. 163.
\textsuperscript{127} Neufeld, pp. 186 & 242.
\textsuperscript{128} Klass, p. 54.
\textsuperscript{129} Neufeld, p. 186.
Over time, the solid fueled missiles, Polaris and Minuteman, won out over the more cumbersome liquid fueled ones. The IRBMs were all withdrawn from Europe by July 1963. All the Atlas and first generation Titan's were gone by June 1965. But the liquid rockets had an inherent performance advantage. This made liquid fueled rockets a good tool for reaching into space. The Air Force was able to use all of its missiles (Atlas, Thor and Titan) as boosters for launching objects into space. Note that the Army's Jupiter is not on this list. Nonetheless, some good did come from the Thor/Jupiter competition. The Army developed an ablative nose cone for re-entry. This is the system used in all military re-entry vehicles today.

The U.S had started six missile projects within three years of each other. In retrospect, Herbert York felt that we only needed three: Titan, Polaris, and Minuteman. Atlas was unnecessary because the Titan, a more ambitious project, was so successful. York also thought that Thor and Jupiter were not needed as stop gap measures. But this is only true because the programs were so successful and because the Russians were not as far along as we believed. If the Russians had deployed ICBMs and if Titan had failed, Atlas would have been needed until Minuteman and Polaris were deployed. If Atlas too had failed, either Thor or Jupiter would have been needed until Polaris and Minuteman were deployed. Having six missile projects was very expensive and wasteful, but it did increase the chances that an IRBM and an ICBM would be available as soon as possible.

By the end of the 1950's the Air Force was doing well in the competition for space access. The Air Force had three rocket programs to draw upon. The Army's role had been constrained to a single rocket program, which only rivaled the Air Force's smallest booster. The Navy had gotten a piece of the strategic bombardment mission, but was out of the booster race altogether.

General LeMay's strategy for defeating the Army had worked. The Air Force had been slower than the Army or Navy but had built boosters larger than the Army.

130 Neufeld, p. 186.
131 McDougall, p. 129.
132 Armacost, p. 146.
133 York, pp. 97 & 102-103.
effectively upstaging the Army and gaining control of all land-based missiles. The Navy had used flexibility to obtain the SLBM role, but was out of the space launch business. As the age of manned spaceflight dawned, the Air Force seemed ideally positioned to be the service to compete with the Soviet Union in space.

10.2.4 Changing of Opponents: The Army and Navy Out, NASA In

In the early days of space flight, the Eisenhower administration had a problem. The “Bomber Gap” and “Missile Gap” had demonstrated the need for good intelligence on the Soviet Union. The solution to this problem would be reconnaissance satellites. But the right to overfly other countries was not yet established. What it needed (as with Vanguard) was a civilian, science-oriented space program. The successful launch of the first artificial satellite, Sputnik, on October 4th, 1957 had boosted the Soviet Union’s prestige and signalled the beginning of the space race. It also proved that space has enormous political and psychological value. An open civilian space program could help U.S. prestige. ICBMs and reconnaissance satellites were seen to have military value, but space flight was considered to be largely a scientific and political enterprise. President Eisenhower also liked the idea that no service would control this program.\textsuperscript{134} Initially the president wanted to place control with the Office of the Secretary of Defense (OSD) with the Advanced Research Projects Agency (ARPA, now DARPA), but was later persuaded by Congress and his advisors to use a civilian organization.\textsuperscript{135}

The civilian organization he chose was the weak, underfunded, and disorganized National Advisory Committee for Aeronautics (NACA). NACA had been created in 1915 when it was realized that the U.S. was behind the other major powers in the field of military aviation.\textsuperscript{136} Its research programs had done a great deal to keep U.S.

\textsuperscript{134}McDougall, pp. 171-174.
\textsuperscript{135}Stares, pp. 41-43.
aeronautics up-to-date with the latest developments in aviation technology. During World War II, NACA had doubled in size.\textsuperscript{137} NACA had a unique organization, headed by a large committee of unpaid aviation experts. The organization was very conservative, but it did excellent aeronautical research.

But by the mid-1950's, the organization was adrift, jet propulsion was becoming routine, and there was clearly a future for spaceflight. But the NACA was unsure of its role in rocket research and had been eclipsed by the military rocket programs.\textsuperscript{138} NACA had expected to grow again during the Korean war. Instead, it found itself being denied funding increases. Secretary of Defense Wilson was not particularly interested in R&D. NACA was having difficulty retaining engineering talent because industry was paying so much better.\textsuperscript{139} Here we see an illustration of Thompson's ideas about why organizations like to grow. They prefer to increase in size and prestige, this allows them to pay, promote, and retain good people. NACA was doing just the opposite in the 1950's. Although they continued to do good research, they were losing the competition for funds in Congress.

Within NACA was a "Frontier Faction" that believed in more aggressive programs and in spaceflight research. They rebelled against the conservative leadership, which was unwilling to participate in rocket development.\textsuperscript{140} As the military services created or contracted for their own space research facilities, NACA changed. A new chairman, James Doolittle, was elected. NACA began to improve its relations with Congress and when the question of the first manned space program came up in 1958, NACA began aggressively touting itself as the natural civilian space agency.\textsuperscript{141}

NACA was converted into the powerful, large, well funded and well directed National Aeronautics and Space Administration (NASA). As one person put it NA\$A became NA\$A. The old NACA committee was replaced by a single administrator who was responsible to the president. The NACA protested, but Congress felt that only

\textsuperscript{137} Roland, Alex Model Research: The National Advisory Committee for Aeronautics NASA. Washington D.C., 1985, pp. 259-260
\textsuperscript{138} McDougall, pp. 75 & 164. NACA did not participate in project Vanguard (see Levine p. 22).
\textsuperscript{139} Roland, pp. 259-275.
\textsuperscript{140} Levine, pp. 18-19.
\textsuperscript{141} Roland, pp. 283-292.
a more centralized organization could get things done quickly and Congress wanted a space agency that could compete with the Soviet Union in the space race.\textsuperscript{142}

Eisenhower had regretted allowing the services to develop their own rocket programs rather than putting all missile development in the DOD. He had created ARPA to centralize all military space R&D, but it had failed to prevent continued interservice rivalry. Now ARPA was in competition with NASA, and the Eisenhower administration decided in favor of NASA.\textsuperscript{143} The military rocket programs were now stripped of many of their most promising facilities, which were then transferred to the new NASA. Of all the services, the Army got hit the worst. As historian Walter A. McDougall puts it: "To build up NASA, Glennan [head of NASA] and the NSC resolved to reallocate American space resources. Their target—and the loser—was the Army."\textsuperscript{144} And, to a lesser extent, the Navy lost as well.

NASA was created out of NACA in August 1958. It was awarded a very large set of facilities. From NACA it received the Langley and Ames Aeronautical Labs, the Lewis Propulsion Lab, the High Speed Flight Station at Edwards Air Force Base, and the Wallops Island rocket range. From the Navy it got the Viking rocket program, as well as the Vanguard rocket program with its satellite tracking network. From the Advanced Research Projects Agency (ARPA), it got all the lunar programs and satellite development facilities at Huntsville. From ABMA it got the million pound thrust rocket development program. In addition, Congress authorized the creation of the Goddard Space Flight Center.\textsuperscript{145}

Both the Army’s Doctor von Braun and the Air Force’s General Schriever wanted the large rocket program. However, both the Secretary of Defense and ARPA felt that there was no military justification for the rocket.\textsuperscript{146} The civilian view of space was: if it was big, grandiose and publicity oriented, then NASA got it. The \textit{Air Force} was only awarded those projects that had a clear military justification. This thinking

\textsuperscript{142}Roland, pp. 297-299, and Levine, pp. 42-43.
\textsuperscript{143}Roland, p. 249 and Levine, pp. 35-41.
\textsuperscript{144}McDougall, p. 198.
\textsuperscript{145}Manno, pp. 63-62, and McDougall, p. 196.
\textsuperscript{146}McDougall, p. 196
was to plague the Air Force’s manned programs from this point onward and to make NASA the big winner in this area.

With the exception of the sub-based solid rocket missiles, the loss of Vanguard meant the Navy was now completely out of the booster business. The founding of NASA also was the end of the Army’s more substantial rocket program. In October 1958 the Jet Propulsion Lab (JPL) at the California Institute of Technology, funded largely by the Army, was transferred to NASA. In September 1959, the DOD assigned all military space operations to the Air Force and the Army’s Saturn project began to run into funding problems. The Army resisted, but in July 1960, Von Braun and his team were transferred to NASA. The Army too was now out of the booster business.

The result was that by 1960, the Air Force was the undisputed military service in charge of space operations. All the boosters to be used for launching satellites from this point onwards would be derivatives of Air Force rockets. The Air Force had won its struggle against the other services for access to space. However, the new civilian agency became the toughest competitor yet. We will examine the Air Force/NASA competition over manned flight in the next section.

NASA would go on to develop the Saturn V, the largest rocket ever produced in the U.S. The Saturn V was also the lowest cost rocket ever built in the U.S. in terms of cost per kilogram launched (see Table 6.5 p. 190). But after the Apollo missions, there were no large payloads to lift. The last Saturn V was used to launch the Apollo/Soyuz mission in the 1970’s. Without large payloads to launch, the Saturn V could not be justified. The Russian Energia rocket is suffering from this same problem today.

The only other new space booster ever built by the U.S. was the Space Shuttle.

---

147 Huntsville became the George C. Marshall Space Flight Center. Von Braun was not transferred with his team. General Medaris and ABMA blocked the transfer for over a year. Medaris claims that he opposed the transfer because initially NASA only wanted half the von Braun team, and that by waiting a year, the entire team could be transferred. But this seems to be an excuse after the fact (see Medaris, pp. 243-247). A presidential order was required to re-assign von Braun to NASA. With this final blow, general Medaris retired from the Army (see Manno, p. 63, and McDougall, p. 198). Medaris left to become the President of the Lionel model train company and later became an Episcopal Priest “Father Bruce” (See Killian, p. 127).
discussed in further detail in the next section. In the 1980’s, NASA and the Air Force jointly funded the development of the Advanced Launch System (ALS). This was to be a new booster, built from scratch, rather than another upgrade of the Atlas, Thor, or Titan rockets. It was hoped that the ALS would reduce launch costs by an order of magnitude to $660 per kg. But the project was converted to a pure research effort in 1989; no rocket was built. The reason was the annual development price of $1.5 billion.\textsuperscript{148} More recently, in 1992, another new booster, the National Launch System (NLS), was also cancelled.\textsuperscript{149} NASA and the Air Force were not willing to pay for them. Today, with the exception of the Space Shuttle, the U.S. relies entirely on derivatives of the Air Force missile programs of the 1950’s: Thor (now Delta), Atlas, and Titan.

10.2.5 Summary of Booster Development

We can now analyze the behavior of the services during the period of booster development. First of all, large technological projects like rocket development will find adherents in any service. Pro-missile groups emerged in all three services, as well as inside the NACA. But these forces always encounter resistance within that organization. Rocket efforts encountered resistance in all three services: the NACA committee resisted moving into space research; pilots in the Air Force wondered why they were building systems without cockpits; Navy submariners would rather have fewer boats than carry missiles; and even in the Army, some referred to the Jupiter as the “world’s most expensive roadblock.”\textsuperscript{150} Each service had a pro-space minority facing a conservative business-as-usual majority. The relative strength of these two forces—as well as the intervention of civilians and senior officers—seems to have determined the behavior of the service.

Through the early development of missiles, the Air Force tended to react to the

\textsuperscript{148} Sourth, Bruce “U.S. Military to Increase Reliance On Space Systems in Coming Decade” Aviation Week & Space Technology March 19th, 1990, pp. 187-188.

\textsuperscript{149} Actually, these programs are never cancelled, they are just made into “research efforts” where not hardware is ever built. Perhaps they would fare better if they changed the name when they applied for funding.

\textsuperscript{150} York, p. 83.
developments of others. Only after significant civilian intervention allowed the space enthusiasts within the Air Force to pursue their interest without interference from the pro-bomber group, was meaningful progress made. The reason for Air Force resistance is that it was busy building the world’s largest strategic bomber fleet at the time. Missiles seemed a faraway solution to a problem that could be solved immediately with bombers. Further, a successful ICBM might threaten the bomber force, which had given the Air Force a independent existence and the largest share of the defense budget.

Despite this lack of initiative, the Air Force became the dominant service in booster development. Everyone competed with the Air Force in booster development. But the Air Force was always second: the AAF emerged from World War II behind the Army and Navy in missile development; the Air Force was the second service to propose a satellite research project, responding to the Navy BuAer; the Air Force developed several large liquid fueled rockets, after the Army did it; and the Air Force moved from solid fuel research into solid fuel ICBM production, after the Navy began its Polaris project. The Air Force usually defeated the other services for control, but it always seemed to be responding to the research efforts of others. The Air Force believed it should control missile technology, and for the most part it did; but it lacked initiative.

In contrast to the Air Force, the Army and Navy rocket programs represented a way of breaking the Air Force monopoly on strategic bombardment: the sooner missiles replaced bombers, the sooner they would be on a more even footing with with Air Force. Consequently, the Army and the Navy encountered fewer obstacles within their own service. Beard describes this effect:

It should be noted however, that neither the Army nor the Navy suffered the internal strains and bitterness that beset the Air Force during the development and introduction of ballistic missiles. The most immediate explanation is simply that the missiles did not threaten any established Army or Navy weapon. Without harming the central purposes of either service, ballistic missiles offered the opportunity of broadening their
roles.¹⁵¹

There was resistance to missile development in both the Army and the Navy. But there were strong organizational incentives to proceed as well. The Army felt it was losing funds to the Air Force, and needed to get into the missile field to compete.¹⁵² The Navy also wanted an increased strategic bombardment role.¹⁵³ Some in the Navy feared that in a direct confrontation with the Air Force, the Navy would lose as it had in the late 1940’s. But this time, the Navy was able to use the Army/Air Force competition to get what it wanted.

Another important factor in the competition is that the Air Force was viewed as the natural missile service. Despite the fact that it was often behind the Army or the Navy in development, the Air Force argued for and got a dominant position in the missile business. The Army and the Navy seemed to sense this early on. Initially, they allied to keep the Air Force from becoming the dominant service, and they failed. The Navy defected and helped the Air Force to push the Army out of the IRBM mission. Civilians sided with the Air Force when it came to assigning missions. Air Force political assets were very strong.¹⁵⁴ The Air Force was building a huge bomber fleet with the lion’s share of the defense budget. Its contractors gave it a ready-made lobbying group. With the support of the Navy, the Air Force had a majority in the JCS as well as the sympathy of the Chairman of the JCS. Despite the fact that the Army was ahead in missile development and had a proven rocket development team, the Atlas, Thor, Titan, and Minuteman were all “naturally” assigned to the Air Force. The Army was simply unable to compete with the Air Force’s ability to get missile assignments and missile funding. Their strategy of being first—first V-2 launch in the U.S., first large U.S. booster, first U.S. satellite, and first U.S. manned launch—failed. The Navy was able to survive with the SLBM mission by siding with the Air Force against the Army. Later the Navy was able to offer a capability that

¹⁵¹Beard, pp. 230-231.
¹⁵²Armacost, pp. 44-46.
¹⁵³Both the Army and the Navy had some atomic weapons. The Army acquired an atomic cannon (a cannon which fired atomic shells) and the Navy had atomic bombs aboard its aircraft carriers.
¹⁵⁴Armacost, pp. 84-92.
the Air Force Minuteman couldn’t match: invulnerability to a precision first strike. But the Air Force emerged from the 1950’s as the only military service with a space launch capability.

One can see a difference between the Navy and the Army in their approach to rocket development. The Army strategy of being first and establishing a reliable system failed. The Navy strategy was to be politically astute and to be more innovative in the projects it pushed. The Navy survived the 1950’s with a missile role, the Army did not.

Those services that were losing the struggle for funding were the most innovative, as Clark would predict. But we also see that their innovations, in turn, create potential threats to the core activities of the winning service (the Air Force), which spurred it to act.¹⁶⁵ NACA serves as an extreme example of how an organization that is losing the funding competition can overcome its conservative majority to seize the initiative. Without outside prompting, NACA converted itself from a conservative, introverted aeronautical research organization into an aggressive space agency.

Another important lesson of this period is that civilians can have a tremendous impact in the area of military space operations. Civilians have the power to restructure service and agency organizations to achieve desired ends. The creation of the WDD and NASA are good examples of this. But in other ways, civilian control was limited. Repeated efforts to prevent missile competition between services failed completely. Every missile system was built, even when it became apparent that there were redundancies in the missile programs. Of course today, the DOD has much more power than it did in the 1940’s and 1950’s and the services tend to be less openly competitive. We will discuss this point further at the end of this chapter.

A final lesson is that in order for a program to succeed, a group within the service must come to identify with and defend it. This may seem obvious, but it is important nonetheless. After the civilians are no longer interested or are interested in cutting costs, the program will only survive if a group is willing to fight for it, to find new

¹⁶⁵ The Air Force responded to Army and Navy rocket programs with attacks, but also with alternative programs. The Navy responded to Air Force attacks on Polaris by producing new innovations like double crewing of its submarines.
justifications for it, and to attack other programs. For example, the Army fought to retain both the Redstone Rocket and the Jupiter missile. The Army was a resourceful defender of both of these programs, keeping them going much longer than the civilians or the Air Force wanted. As Rosen states, innovation often requires a service organization in which officers can make their careers. Without an organizational interest, service interest in the mission will decline with civilian concern.

10.3 Manned Missions: NASA Defeats the Air Force

Of all the areas of space considered in this dissertation, manned space flight most closely represents the Air Force's ideal. Carl Builder characterizes the Air Force as interested in technology, specifically men piloting machines. By definition manned spaceflight involves men piloting very costly and technologically intensive machines. One would expect the Air Force to think of manned flight as the Air Force's primary mission in space. It is not too surprising therefore to learn that, the Air Force was, and remains today, very interested in manned space flight. The Air Force does and will continue to pursue this area without encouragement. Unfortunately, manned spacecraft offer little military utility when compared with far less expensive unmanned spacecraft.

By 1960 the Air Force had defeated the other services in the struggle to achieve access to space. The Air Force owned all the boosters capable of putting men into space. Only NASA stood between the Air Force and total control of the manned U.S. space program. The Air Force fought tenaciously for the manned spaceflight mission. In contrast to ICBM development, the Air Force pushed for increases in funding instead of taking a "go slow" attitude. But NASA and the civilian leadership that created it proved too powerful. Today, the Air Force has no manned space system.

---

10.3.1 The Military Utility of Manned Missions

Before proceeding to the history of manned spaceflight, let us emphasize that manned spaceflight has no net military utility when compared with automated spacecraft. This is because humans in space require vast resources while adding little to the overall performance of the vehicle. Here is a list of human requirements in space:

First, boosters that launch humans into space must be "manned rated." This means that they must be much more reliable than the boosters used to launch machines. Reliabilities of 90 to 95 percent are acceptable when launching multi-million-dollar pieces of hardware, but unacceptable when launching humans. Having astronauts die at a rate of 5 to 10 percent per flight would be a very bloody space effort.

Increasing reliability beyond the 95% level involves great expense. Rather than pay the prohibitive costs of increasing reliability, satellite manufacturers are willing to pay for the occasional loss of an expensive satellite. But with humans, this is not an option. Man-rated boosters are much more expensive per pound launched than normal boosters, as the Space Shuttle demonstrates.

Second, humans in space require extensive, expensive, and heavy support systems. Humans require a pressurized environment, oxygen, carbon dioxide removal, water, food, temperature regulation, and waste disposal. All the machines that provide these services must be very reliable, because if any one of them fails, the humans die. Both humans and electronics are vulnerable to radiation. In a manned spacecraft the entire capsule must be shielded, instead of the compact electronic devices that could be sent instead of humans.

Because of the expense and weight of life support systems, and because of their consumption of power and oxygen, human flights cannot last very long. Even if these problems were overcome,\(^{157}\) human physiological changes make extended space flight difficult, requiring additional exercise, cleaning, and medical facilities. The multi-year flights of *Viking* or *Voyager* would have been impossible with human crews.

Finally, humans must be returned to Earth at the end of the flight. Allowing

\(^{157}\text{In the future, closed biosphere systems may be developed which can recycle wastes and consume only heat and light.}\)
humans to gradually die at the end of a mission — as we do currently with the computer crews of our spacecraft now — would also be unacceptable. This means that manned spacecraft must have the ability to return to Earth orbit (if it ever left Earth orbit) and then to de-orbit. Re-entry must be carefully done, because too much shock or heat is lethal for humans. Elaborate, protective re-entry capsules must be constructed, with parachutes for descent, and either flotation for landing in the water or last-second retro-rockets for landing on the ground. All this hardware must be launched, maintained, and carried throughout the mission. It too must be man-rated.

Humans do have certain advantages over machines in space. They have a manual dexterity much better than any machine, they are capable of flying spacecraft when it is out of communication with controllers on Earth, and they can improvise solutions to unexpected problems. The Air Force is always quick to point out the advantages of having a human at the scene. This is very much a pilot’s perspective.

But the costs far outweigh the advantages. For the cost of sending one human into space who might be able to improvise if something goes wrong, one could send hundreds of automated probes to ensure success of the mission, and to do much more.

Manned flights do provide one thing that machines cannot: prestige. Manned spaceflights have provided political value by demonstrating spectacular technological prowess. The launch of Sputnik, the space race, and the Moon landing should be proof enough that manned flights do provide international prestige. Manned flights capture the imagination of people and are often easier to fund than unmanned flights; but manned flights’ popularity declines as mission become routine, often making them much harder to maintain than unmanned flights.

10.3.2 NASA Versus the USAF: Early Struggles

As we saw in Section 10.2, NASA and the Air Force emerged as potential rocket builders. It was up to the Eisenhower administration to decide who would get the first manned spaceflight project: Project Mercury. In August 1958, President Eisenhower decided in favor of NASA for two reasons.
First, Eisenhower felt a U.S. space program should be a civilian program. According to McDougall "The United States' image required that such a high-profile program be civilian." At this time the U.S. was trying to gain international acceptance for its reconnaissance satellites (see Section 10.2.3, p. 308). This may also explain why such a "high-profile" program had to be civilian.

Second, the Air Force's plans for manned space missions were unrealistic. The Air Force's proposed manned program called for "rocketing pilots in 'aerospace planes' to 'orbital bases' for purposes that could be better fulfilled by instrumented satellites. This only convinced Eisenhower and his advisors that the USAF had to be restrained, not encouraged."

Eisenhower had overseen huge increases in Air Force budgets, but now he was trying to reign it in. From early 1957 onward, Eisenhower came to view the growth in Air Force weapons requirements as out of control. Increasingly he attempted to limit force requirements, but was unable to do so. This explains the instances in this history where Eisenhower attempts to limit Air Force control. The manned mission went to NASA, and as we shall see in Section 10.4 (p. 333), Eisenhower did his best to give the reconnaissance satellite mission to the CIA instead of the Air Force.

After this decision, the Air Force's General Schriever joined with the head of Navy research to argue that NASA should not be allowed to contract directly. They felt that this power should remain exclusively with the military services. The administration assured the services that NASA was intended for scientific exploration of space and that it would not interfere with ongoing military space projects. The services dropped their objections.

The Air Force accepted these defeats and waited for a new administration to come into office. Eisenhower was not interested in a large space program. It was

---

158 McDougall, p. 200.
159 McDougall, p. 200.
161 This is consistent with the move limited role of NACA: the organization which became NASA. NACA was a research establishment which served industry and the military.
162 Manno, p. 64.
rumored that Eisenhower planned to cancel the manned space program when Project Mercury ended.\textsuperscript{163} The Kennedy Administration seemed much more enthusiastic about space, and the Air Force had big plans. During the first months of the Kennedy administration, in March 1961, the Air Force issued a top secret report on space (the Gardner Report). This report underlined Soviet achievements in space, claiming that a purely civilian space program amounted to a form of unilateral disarmament. It recommended that a new Air Force Systems Command be created and that it be charged with developing manned spaceflight, reconnaissance systems, space weapons, large boosters, space station, and a lunar landing sometime during 1967-1970.\textsuperscript{164} A ten-year space plan was issued by the Air Staff in September 1961, with similar goals:

In addition to proposing passive satellite systems which had already been justified, the plan presented an urgent requirement for a satellite interception system, space based ballistic missile defenses and fast-reaction space bombers that could re-enter the atmosphere. Above all else, however, the Air Force wanted to demonstrate a manned military capability in space.\textsuperscript{165}

NASA and its civilian backers in Congress began to worry that NASA might be placed under DOD control, but they were assured by Kennedy that NASA would retain its independence. In fact, the Air Force's general Schriever appeared to be suggesting parallel space programs. He spoke of the differences between military and civilian space needs: first, the military would need many more vehicles to perform day-to-day missions while NASA's vehicles would be few and exploratory; second, military spacecraft would need to be long-lived and would be launched repeatedly, while NASA vehicles would be one-shot affairs; third, military systems would need to be simple and easy to operate while NASA's would be scientific and complex; fourth, military launches would be more time critical; and fifth, military system users (the Air Force) would be different from their designers (aerospace contractors), while for NASA they would be one and the same. The Air Force's position was that more funding

\textsuperscript{163}Levine, p. 68.
\textsuperscript{164}McDougall, p. 313.
\textsuperscript{165}Stares, p. 74.
was needed for space. Initially, NASA could develop the building blocks to space, but later, the two programs would naturally diverge. The Air Force maintained that a civilian-only program would threaten U.S. security.\textsuperscript{166} Ironically, General Schriever's position strengthened the case for a NASA-only manned space program. It took all the mission characteristics that make a manned mission easier to fund and attributed them to NASA. Manned missions were one-shot affairs: enthusiasm for them quickly vanished once the first flight was made. Manned spaceflight was also justified on scientific grounds. The Air Force was asking for non-scientific and repetitive manned missions. It had fatally underestimated the difficulty of funding manned missions.

NASA was persuaded by the Air Force's complaints to come to an agreement. The deal was given Secretary of Defense McNamara's blessing. DOD would have primacy in the areas of missiles, reconnaissance, military communication satellites, navigation, geodesy, and satellite inspection and interception. The two would have a joint role in launch vehicles and manned spaceflight. The Air Force was given the X-20 Dyna Soar manned system to develop. This was a shuttle-like winged re-entry vehicle launched by a Titan booster. Neither DOD or NASA would initiate new launch vehicles without the other's consent. Solid rockets were to be "a USAF show."\textsuperscript{167}

This represents the high point of USAF involvement in space. It had defeated the other services in the battle for access. Now, it seemed to have at least a share in the manned spaceflight program. It also seemed clear that the civilians were finally willing to spend the money necessary to develop an extensive space program. The Air Force hoped that NASA would revert to the status of the old NACA, leaving the field clear for the Air Force to lead the way into space.\textsuperscript{168} From the Air Force's viewpoint, things were looking pretty good in 1961.

\textsuperscript{166}McDougall, p. 314.
\textsuperscript{167}McDougall, p. 315. The one exception was the Polaris missile, which the Navy retained, despite Air Force efforts to obtain operational control.
\textsuperscript{168}Stares, p. 61 and McDougall, p. 312.
10.3.3 NASA Takes Off, USAF Is Canceled

The Air Force had won the inter-service struggles over launch vehicles and had found an administration willing to spend money on manned spaceflight. But all the money went to NASA—a new civilian agency.

The Air Force viewed itself as having a future in space. General LeMay wrote “The conquest of Space will be won by men with wings.” Defense Secretary McNamara’s philosophy was to allow NASA to do exploratory research, while requiring the Air Force to demonstrate a military requirement for any space system it proposed. The result was that little money went toward Air Force manned spaceflight because there was no military requirement for manned space systems. McNamara was fond of saying space is not a mission, or a program, or a cause, it’s just a place. Every manned system the Air Force proposed could be undercut by a far less expensive un-manned system.

For the first 18 months of the Kennedy administration, NASA and the USAF got along well. Then the new administration “lowered the boom” on what it considered to be de-stabilizing programs: SAINT (a satellite interception/inspection device), R&D on orbital bombardment, nuclear rocket propulsion, and nuclear ASAT research were all canceled.

At the same time McNamara gave the Air Force something it wanted, stating that the USAF would have an equal or dominant role in the new Gemini manned space program. NASA reacted quickly, claiming that the moon project would be jeopardized and that this would signal the militarization of the U.S. space program. In the end, NASA chief Webb and McNamara agreed to give the Air Force a smaller role in Gemini dubbed “Blue Gemini.”

By Fall 1962, the Kennedy administration had developed a hard nosed attitude toward military space programs in general and the Air Force’s manned mission pro-

---

169 LeMay and Kantor, p. 551. For more descriptions of the Air Force role in space, see pp. 523 & 538-539.
171 McDougall, p. 336.
posals in particular.\textsuperscript{174} The X-20 was now in trouble. In 1962, funding was reduced and the projected first flight was pushed back to 1966. Finally, in October 1963, the X-20 was canceled in favor of a relatively new project, the Manned Orbiting Laboratory (MOL).\textsuperscript{175} This was a Gemini capsule with an add-on space station, launched by the Titan booster. Equipped with a 90 inch telescope, it was to be used by the Air Force to perform reconnaissance. But the MOL project was the administration’s way of placating the Air Force after cancelling the X-20.\textsuperscript{176} This tactic was used repeatedly by the civilian administrators to kill military space programs. Each cancellation was accompanied by emphasis on a newer program, which itself was later canceled when it came time to build expensive hardware.

The X-20 cancellation was quite a blow to the Air Force. Throughout its development, the Air Force had placed a higher priority on this system than either ASAT systems or the MOL.\textsuperscript{177} The X-20 was a winged, piloted vehicle as well as a rocket into space. The attraction of this vehicle was very strong, but it could not be justified on purely military grounds.

Of course, the Blue Gemini manned reconnaissance program was also hard to justify. A man in orbit with a camera could do little more than a camera alone. And the man required an enormous amount of hardware to sustain him and to return him to Earth. Blue Gemini was deleted from the budget in January 1963.\textsuperscript{178}

The MOL however continued to be funded through the Johnson administration, but never at the level necessary to keep it on schedule. Development was stretched out, but $1.5 billion for MOL was approved in August 1965. By 1966 costs had risen to $2.2 billion and by 1969 the first of five MOLs were expected to cost $3 billion each.\textsuperscript{179} The program survived into the Nixon administration only to be canceled by Secretary of Defense Laird in June 1969, the same year NASA landed men on the Moon. The KH-9 reconnaissance satellite had undermined any justification for the

\textsuperscript{174}Stares, p. 79.
\textsuperscript{175}McDougall, pp. 340-341.
\textsuperscript{176}Stares, pp. 96-98.
\textsuperscript{177}Manno, p. 151.
\textsuperscript{178}Stares, p. 79.
\textsuperscript{179}Klass, pp. 149 & 169.
MOL. By then, it was clear that NASA was the only agency that was going to get the money to put men into space. As Paul Stares puts it:

While the Air Force’s participation in NASA activities was consolidated during the Kennedy administration, its influence actually declined. The tenfold leap in NASA’s appropriations stemming from President Kennedy’s commitment in May 1961 to land a man on the moon by the end of the decade not only increased NASA’s political constituency but also sealed the primacy of NASA’s manned space flight programme over the Air Force’s.  

10.3.4 Tight Budgets and Forced Accommodation

By the early 1970’s, NASA’s situation had drastically changed. NASA had been created by Eisenhower’s enthusiasm for a non-military space program. It had been boosted by Kennedy and Johnson’s commitment to go to the Moon, and the tremendous amount of prestige and money that came with it. But now NASA was facing a decline in civilian support. The number of Moon missions were reduced, and the last Moon walks received poor television ratings. NASA’s budget was cut. Manned missions continued with Skylab and the Apollo/Soyuz (using the last of the Saturn V rockets), but the inertia of the Moon project was gone. Science had always been a secondary objective of NASA, manned spaceflight always came first. But once the men had gone somewhere, there was little interest in repeat performances. As with military missions, there was not justification for manned scientific expeditions.  

Originally NASA had planned for an Earth-to-orbit shuttle, a space station, and a space-station-to-Moon shuttle as part of a permanent Moon base and the start of a mission to Mars. Now it was left with only the Space Shuttle, and it was having

180Stares, pp. 97-98, 159-160.
181Stares, pp. 61-62.
182Is was rumored that Eisenhower planned to cancel the U.S. manned project after Mercury. See Levin p. 68.
183Levin, Chapters 6 & 7.
difficulty funding even that.\textsuperscript{184} Short of funds, NASA reluctantly turned to the Air Force for help in 1970. As Burrows puts it:

The old-timers at NASA had come to cherish the agency’s civilian orientation ... But there had not been money to go around for all the space programs everyone wanted at the end of the sixties and into the seventies, so NASA had been forced to rely on Air Force funding for part of the Shuttle's development. There were some at the space agency who tended to think of their relationship with the Air Force as being roughly equivalent to that of an impoverished prodigy who is forced to live off the largess of a well-heeled but slightly unsavory cousin. But they took the money.\textsuperscript{185}

For the Air Force, this was another chance to get into the manned spaceflight business. It was now in a position to make demands, and it did. The conditions it imposed upon NASA illustrate the Air Force's continuing obsession with manned flight. The Air Force asked for and received a Shuttle launch facility of its own at Vandenberg Air Force Base in California. The Shuttle itself was substantially redesigned to meet Air Force requirements. One of these requirements was that the Shuttle be capable of lifting off into a polar orbit, and then before completing one orbit, to return to land at the original launch site. This was intended to allow the Shuttle to make quick, single-orbit reconnaissance flights from Vandenberg.\textsuperscript{186}

The Air Force requirements were a combination of the X-20, Blue Gemini, and the MOL in one package. It wanted all the manned systems it had been denied in the 1960's. It wanted a manned space cruiser. If the cruiser looked more like a truck than a sports car, that was fine, just as long as the performance was there. By 1970, the overhead reconnaissance mission was being performed by satellite. In fact, for the previous nine years it had been performed by satellite. But no matter, as far as the Air Force was concerned, there was a need for manned reconnaissance missions, launched from a facility that was completely under Air Force control.

\textsuperscript{184} Manno, p. 152.
\textsuperscript{185} Burrows, p. 203.
\textsuperscript{186} Manno, p. 152.
NASA intended the Shuttle to become the primary means of launching satellites, something the Air Force had been doing with expendable un-manned boosters. With the Shuttle, it could convert to launching satellites with a manned system.

The Air Force went with NASA before Congress to get funds for the re-designed Shuttle. By 1972 the Shuttle was a joint NASA/DOD project. As the first Shuttles began flying in the 1980's, the Air Force once again came close to realizing its dream of military manned missions. The Vandenberg facility was nearly complete when the Challenger disaster in 1986 changed everything. The long delay before a shuttle was to fly again, combined with the reduced payload, higher costs, and lowered expectations of Shuttle reliability made expendable boosters once again the primary means for orbiting satellites. The Air Force was forced away from the Shuttle as a satellite launch vehicle, investing instead in a new generation of expendable launchers. The Shuttle program was scaled back and the Vandenberg site was put into moth balls as an economy measure. Once again, 25 years after Gemini and the X-20, the Air Force had manned spaceflight snatched away. Once again the Air Force was reduced to lifting satellites into orbit with expendable boosters.

The history of the Shuttle demonstrates a number of points about spacecraft and the Air Force. The tremendous costs of spacecraft development encourages even the most independent service or agency to cooperate with others to get the necessary funding. It also points to the continuing Air Force dream of manned spaceflight, still unfulfilled.

Today, the only new manned vehicle under development is the National AeroSpace Plane (NASP or X-30). This too is a joint NASA/Air Force project. NASP is a single-stage-to-orbit vehicle. Advertised as a high-tech airliner, the NASP design calls for putting one or two crew members into orbit. Design is proceeding, but construction has not yet begun. As we have seen with so many space projects, R&D can go on for ever, but the real cash crunch comes when vehicles are actually built.

Thus far, after five years and $1 billion in funding, NASP has not yet moved beyond designs, computer simulations, and wooden mock ups. Construction is expected

---

to start in 1993 and to cost $4-8 billion. Waiting in the wings is the Single-Stage-to-Orbit (SSTO) project, which will appear as a cheaper alternative just as funding for the X-30 is expected to rise sharply.\textsuperscript{188} In other words, the X-30 may well suffer exactly the same fate as the X-20: canceled in favor of a newer, less costly alternative which is not yet at the expensive construction phase.

10.3.5 Summary of Manned Missions

From the Air Force perspective, the history of manned space flight has been a very frustrating one. The most attractive space prize, manned spaceflight, was stolen from the USAF by NASA. Every time the Air Force has come close to launching a manned vehicle of its own, the lack of a military justification has undermined and destroyed the project. The Mercury, X-20, Blue Gemini, MOL, and the Vandenberg-based Shuttle are all examples of manned systems that might have gone to the Air Force, but which were moved to NASA or canceled before taking flight. Despite many close calls, the Air Force has never launched a man into space.

The one mission that the Air Force is willing to fight hard for and to fund on its own, manned spaceflight, is the one mission it has never been allowed to perform and should never be allowed to perform. The rest—satellite launch, reconnaissance and ASATs—is small potatoes. Such projects involve sending machines, not men and machines, to perform missions. And while this may be technologically challenging, it does not carry the prestige and excitement of manned spaceflight.

\textsuperscript{188}As \textit{The Economist} puts it:

The SSTO craft is not thought of as a technology provider, like the X-30 ... It is a consumer. Its lightweight materials will come from the X-30 research. The contract calls for craft that take off from a flat bit of concrete and require little more servicing than an up-to-date aeroplane ... It is easy to talk about such things, much harder to do them; but a programme at this stage cannot be expected to do much, and it is at least reassuring that it says the right things. It is saying them at the right time, too. When its preliminary development is done, the X-30 will be reaching the time in its life when it starts to cost a lot of money. A cheap, can-do alternative ... might look extremely appetizing.

10.4 Reconnaissance Satellite Development

The Air Force and the Central Intelligence Agency (CIA) have been the two competitors for the reconnaissance satellite mission. They have competed for control of reconnaissance satellite development, satellite target selection, and data interpretation.

From the late 1940’s onward, the Air Force’s Strategic Air Command (SAC) had a strong vested interest in overhead reconnaissance because assessments of the Soviet threat were driving their bomber and missile deployments. Eisenhower did not trust the Air Force and sided with the CIA to give them the reconnaissance mission. Despite Eisenhower’s bias, the Air Force managed to stay an equal player in this struggle, but never managed to obtain a monopoly. This was a case in which existing Air Force institutions accelerated development rather than inhibiting development.

Today, much of the organizational structure surrounding satellite reconnaissance is secret. Nonetheless, it seems clear that both the USAF and the CIA have access to data and both participate in satellite development. The Air Force alone is responsible for satellite launch and operations. Satellite reconnaissance represents another case where the Air Force had a strong incentive to gain total control of a mission and failed. But the Air Force has been able to fight the CIA to a draw. Thus, the Air Force remains a player in the satellite reconnaissance business, but it must share the field with the CIA.

Because of the highly secret nature of satellite reconnaissance, it is difficult to follow much of the debates over roles and missions. Fortunately, much of the organizational structure of this mission appears to have been created back in the late 1950’s and early 1960’s. Information about that period is much easier to come by. I will concentrate on this period of time in order to derive some lessons about Air Force behavior.
10.4.1 Early Developments in Overhead Reconnaissance and the "Gaps"

The CIA's interest in reconnaissance satellites was simple enough to explain: intelligence gathering is the whole purpose of the organization. Back in 1952, the CIA commissioned the RAND Corporation to study the feasibility of satellite reconnaissance.\textsuperscript{189} The very first U.S. strategic overhead reconnaissance system was the U-2 spyplane. When Eisenhower insisted that the U-2 be kept from the Air Force, the CIA volunteered to run the program.\textsuperscript{190} But CIA ambitions were not limited to aircraft.

The first U-2 flights over the Soviet Union began in 1956. By 1957, results of these flights showed no massive fleet of Soviet bombers.\textsuperscript{191} The "bomber gap" was turning out to be a myth. 1957 saw the surprise launch of Sputnik by the Soviet Union. This triggered fears of a "missile gap." By late 1958, U-2's were reporting no ICBM fields either.\textsuperscript{192} But this source of information was abruptly cut off in May 1960, when a U-2 piloted by Francis Gary Powers was shot down.\textsuperscript{193} Further U-2 flights over the U.S.S.R. were halted.

Any further reconnaissance of the Soviet Union would have to be accomplished by satellite. The first contract for a satellite was let in 1956, and by August 1960 reconnaissance satellite information was coming in. The "missile gap" was also found to be a myth.\textsuperscript{194} In June 1961, the official U.S. estimate of the number of Soviet ICBM's was revised from 120 to 60. By September 1961, the estimate was down to 14.\textsuperscript{195}

\textsuperscript{190}Burrows, pp. 69-70.
\textsuperscript{191}Burrows, pp. 76-77; and Klass, p. 20.
\textsuperscript{192}Burrows, p. 106; and Klass, p. 38.
\textsuperscript{193}Burrows, p. 76; and Klass, p. 67.
\textsuperscript{194}Burrows, pp. 106-107.
\textsuperscript{195}Klass, pp. 104 & 107.
10.4.2 Air Force Motivations

We have already seen in the previous two sections that the Air Force was not particularly enthusiastic about rocket development and that it was denied its one true dream, manned flight. But the Air Force was interested in unmanned reconnaissance satellites because of the strategic bomber fleet. In order to perform long range strategic bombardment, SAC needed a list of targets to bomb. Target lists required detailed information about the locations of airbases, missile sites, and industries. The best means of obtaining this kind of information was via overhead, photo reconnaissance. Thus the driving mission for the Air Force in the 1950's required photos of the interior of the Soviet Union.

Not only did these photos tell where to bomb, they also revealed how many targets there were to bomb. That theoretically determined how many bombers the U.S. needed. Thus, control of photo reconnaissance, and photo reconnaissance interpretation, meant control of bomber force requirements.

Is was for these same reasons that President Eisenhower was determined not to allow the Air Force to control this space mission. Some have argued that Eisenhower's control over U.S. nuclear policy in general and SAC in particular during this period was becoming quite limited.\textsuperscript{196} After the bomber gap and the missile gap, Eisenhower was not inclined to trust SAC's interpretation of photo intelligence.\textsuperscript{197} He was fortunate to have the CIA, an enthusiastic and technically competent organization, to use as an alternative.

10.4.3 Alternative Technologies

Air Force sponsored feasibility studies of overhead reconnaissance produced two types of photo satellite research projects: scanners and bucket droppers. Both systems placed a high resolution film camera in orbit to take pictures of the Soviet Union. The essential difference between the two systems was in the way the image was returned.

\textsuperscript{196}Rosenberg, pp. 43-71.
\textsuperscript{197}Burrows, p. 197.
to Earth. In the scanner type of satellite, the photograph was developed on board and then electronically scanned. The scanned information was radioed to a ground station, much like faxing a polaroid picture. The bucket dropper used a film capsule equipped with a retro rocket and a parachute to physically transport the negatives back to Earth.

The scanner system was less complex because no capsule return to Earth was required, but produced lower resolution pictures because the scanning device introduced more distortion. But the resolution was good enough for area coverage and target identification.¹⁹⁸

The bucket dropper system was more complex and technically more difficult, since the film capsule had to be safely returned to Earth. These difficulties involved more than just the capsule itself. As the capsule descended by parachute, it was supposed to be snatched by an aircraft, with special equipment on the nose.¹⁹⁹ Alternatively, the capsule could be recovered after landing or after splashing down at sea. But the advantage of the bucket droppers was that the actual negatives could be examined, yielding a higher resolution. For detailed technical assessments, this was important.

The Army was also interested in satellite reconnaissance. It had beaten the Navy to putting the first U.S. satellite in orbit. Now, it proposed a satellite reconnaissance system of their own, based on a third technology.²⁰⁰ The satellite would use an early video tape machine to store images for play back when the satellite flew over the U.S.

### 10.4.4 Corona and SAMOS

Eisenhower chose in favor of the CIA before any satellites were launched. In 1958 the CIA was directed to develop a reconnaissance satellite to be launched by a Thor IRBM in 1959: project Corona. Officially the Air Force bucket dropper program was cancelled, but this was a deception. The CIA took over management of the Air

---

¹⁹⁹James Bond film fans will recognize this hardware as the same used to rescue Bond and his heroine at the end of *Thunderball*.
Force's bucket dropper program. Corona information was distributed on a need-to-know bases. Some former managers of the Air Force program were not even told that their project was continuing.\textsuperscript{201} In addition, the transferred Corona program was partly funded from monies set aside for the USAF's SAMOS scanning reconnaissance satellite program.\textsuperscript{202} The USAF was told to abandon its scanner technique,\textsuperscript{203} but continued work on it anyway. The Army plan was also rejected, but the Army did go on to develop television-based reconnaissance satellites (see Section 10.4.6 below).

The result was two reconnaissance satellite programs: one run by the Air Force, the other run by the CIA. Corona was a bucket dropper type satellite and was run by the CIA. SAMOS\textsuperscript{204} was a scanner type satellite and was run by the Air Force.

In much the same way as the Army and the Air Force competed with the Jupiter and Thor IRBMs (see Section 10.2.3 p. 310), each organization championed its system as the one to pursue, hoping to out-perform the other. Each was hoping to be the first to return pictures of the Soviet Union, forcing the other system to be canceled, and to thereby gain control of the mission. But unlike the Thor-Jupiter competition, this struggle produced two very different systems.

\section*{10.4.5 Attempts at Centralization}

In 1960, the National Reconnaissance Organization (NRO) was created.\textsuperscript{205} The plan was to move CIA and USAF efforts in satellite reconnaissance into a single organization, the NRO. Under this re-organization, the duplication in the CIA and the Air Force programs was to be eliminated. Eisenhower was wary of giving the photo intelligence mission to the Air Force. He “wanted to make damn sure”\textsuperscript{206} that the Air Force did not control the NRO. The Air Force was given responsibility for launching,

\begin{flushleft}
\textsuperscript{201}Richelson, pp. 26-28.
\textsuperscript{202}Stares, pp. 44-45.
\textsuperscript{203}Stares, p. 45.
\textsuperscript{204}SAMOS was a name intended to defy being turned into an acronym. The program manager derived the name from MIDAS, and Army satellite program. The mythical character Midas lived on the island of Samos. Despite his efforts, people found an acronym for it: Satellite and Missile Observation System. See Richelson, p. 44
\textsuperscript{205}Stares, p. 44.
\textsuperscript{206}Richelson, p. 46.
\end{flushleft}
controlling, and recovering the satellites (since the bucket dropper system had been chosen, presumably all satellites would require capsule recovery). The CIA was given responsibility for development of satellites and the sensors on them. Despite this directive, the Air Force continued to work on its own system\textsuperscript{207} in much the same way that the Army had continued to work on Jupiter after the directive giving the Air Force operational responsibility over all IRBM's.

In contrast to the Army's experience with the Jupiter, the Air Force's persistence paid off. In 1960, after several Corona failures,\textsuperscript{208} the simpler USAF scanner system was re-considered, and more money was put into SAMOS.\textsuperscript{209} Ironically, in August 1960, the fourteenth Corona satellite successfully returned pictures to Earth.\textsuperscript{210}

Struggles between the Air Force and the CIA continued within the NRO.\textsuperscript{211} While the NRO was supposed to solve the problems of conflict over satellite development and operations, the National Photo Interpretation Center (NPIC) was created to resolve the conflicts over photo interpretation. This was a result of Eisenhower's desire to deny Air Force exclusive control over the interpretation process. An additional argument was that photo interpretation required experienced people. It was felt that military officers would be rotated too quickly, while civilians could make their careers

\textsuperscript{207}Burrows, p. 198.

\textsuperscript{208}In February 1959, the CIA's first bucket dropper, Discoverer-1, was launched and failed (see Klass, p. 92). Its next effort, Discoverer-2 was the first U.S. capsule successfully returned to Earth. Unfortunately, it landed on Spitsbergen, an arctic island off the coast of Norway. A frantic search began, but it is believed that miners from the Soviet Union got to the capsule first (see Richelson, p. 35). Many more failures were to follow.

\textsuperscript{209}Stares, p. 48.

\textsuperscript{210}Richelson, p. 42.

\textsuperscript{211}From 1960 to 1963 the creation of the NRO did succeed in quelling the disputes between the Air Force and the CIA. The first NRO director was Secretary of the Air Force Charyk, with a CIA appointed deputy. Charyk's tenure was "harmonious." [See Burrows, p. 199.] But in 1963 the NRO received a new director, Brockway McMillan. McMillan tried to end the CIA's formal monopoly on R&D. At the same time, the CIA's director, McCona decided to increase the CIA's space reconnaissance R&D relative to the Air Force. [See Burrows, p. 200.] The tug-of-war went on until the National Reconnaissance Executive Committee was created in 1965. [See Burrows, p. 205.] This was a body composed of senior officials who arbitrated between the Air Force and the CIA.

In a further effort to coordinate satellite reconnaissance, the Committee on Overhead Reconnaissance (COMOR) was created in 1967. COMOR's job was, and is, to assign priority to for satellite imaging. Consumers of this information include not only the CIA and Air Force, but the other services and the Dept. of State.
as photo interpreters.\textsuperscript{212} Initially both the CIA and the Air Force used the common agency to coordinate interpretation. But gradually, both the CIA and the Air Force developed their own photo interpretation centers. Today, the NPIC functions as a central depository of reconnaissance photos, which both CIA and USAF interpreters draw upon.\textsuperscript{213}

\textbf{10.4.6 The Competition Continues}

In the Fall of 1961 the Kennedy administration decided to shroud the reconnaissance satellite program in secrecy.\textsuperscript{214} They were afraid that the Soviet Union would object to reconnaissance satellite overflights of its territory and shoot them down, much as the U-2's had been shot down. As with the first U.S. satellite, it was decided that the best defense was to present the U.S. space program as civilian, scientific, and peaceful.

This was a blow to the USAF which liked to publicize its space activities. Now it was told to stop.\textsuperscript{215} The word ‘SAMOS’ was expunged from the public USAF vocabulary, and General Schriever told not to use the word ‘space’ in any of his speeches. At the same time NASA began its highly publicized civilian space program.

In April 1962, the first of the Soviet Kosmos series of satellites was launched.\textsuperscript{216} The Russians were now developing reconnaissance satellites of their own and in April 1963, they agreed that satellite overflights of foreign nations were legitimate.\textsuperscript{217} But the U.S. reconnaissance satellite program was to remain in the black world for the duration of the Cold War.

While the Air Force and CIA were developing scanner and bucket dropper satellites, the Army was developing a third option. This system involved no film at all, but used a television camera to take pictures and to transmit them directly back to Earth. The system, dubbed Tiros, was adopted by the Army in 1957 to perform

\begin{itemize}
\item[I] Richelson, pp. 63-64.
\item[213] Burrows, pp. 208-213.
\item[214] McDougall, p. 272; and Klass, p. 109.
\item[215] Stares. pp. 63-65 & 73.
\item[216] McDougall, p. 272; and Klass, p. 118.
\item[217] McDougall, p. 274; and Klass, p. 125.
\end{itemize}
battlefield surveillance. But as the Army's fortunes in space declined (see Section 10.2.3 p. 310), so did its satellite program. By 1958 Tiros's mission had shifted to cloud imagery, in other words, weather prediction. The first Tiros was launched on April Fool's Day in 1960.\textsuperscript{218} Eventually the program was transferred to NASA, and then to the National Weather Bureau.\textsuperscript{219} As a military mission, weather prediction was later assumed by the Air Force in 1965, when it first orbited its own weather satellite.\textsuperscript{220}

From 1961 to 1963 both the SAMOS and the Corona programs were pushed amid great frustrations. Launchers would explode on the pad, destroying precious satellites. Launchers would work, only to have the satellites fail in orbit. Launchers would work and satellites would take pictures and return them to Earth, only to be lost in the wilderness and never recovered. But information was slowly coming in.

Meanwhile, both the CIA and the Air Force were hard at work on follow-on technologies. The Corona program cameras were designated KH-1 through KH-4. The second generation bucket dropper, the KH-4A, appeared in 1963.\textsuperscript{221}

SAMOS was cancelled in 1962, a costly failure.\textsuperscript{222} The second generation scanner, the KH-5 used a camera developed by the Army in its bid to get into the satellite reconnaissance business. But the KH-5 was also a failure. During 14 attempted launches, only 11 successfully orbited, and only three of those satellites returned pictures. The KH-5 was also cancelled in 1962. Later attempts to make the scanning method would also fail.

The Army participation in reconnaissance satellites died with the KH-5, but the Air Force continued to develop satellites of its own. It switched to the CIA's bucket-dropping technique and produced a system with a better resolution than the CIA's KH-4A.\textsuperscript{223} This was the KH-7 which was used to provide a "close look" at areas of interest identified by the KH-4A satellites. The two systems worked in tandem, each

\textsuperscript{218}McDougall, p. 221.
\textsuperscript{219}Klass, pp. 86-87 & 97.
\textsuperscript{220}Klass, p. 140.
\textsuperscript{221}Richelson, p. 77.
\textsuperscript{222}Richelson, p. 68.
\textsuperscript{223}Richelson, p. 77.
depending on the other.

This tandem arrangement was to continue for two more generations of satellite. The CIA’s KH-4B area satellite worked with the Air Force’s KH-8 close look satellite. The KH-4B and the KH-8 appeared in 1966. The first launch for each of these satellites were less than eight days apart. In 1971 a new kind of satellite appeared, the KH-9 Big Bird, both a bucket dropper and a scanner. Unfortunately, the scanner aboard the KH-9 did not work and was abandoned. Further, the KH-9 did not quite have the resolution of the KH-8, and so KH-8’s continued to work in parallel with the KH-9’s.

The KH-9 is credited with being the first NRO project, that is, neither an Air Force nor a CIA creation. The fact that the KH-9 was an NRO creation is significant. Gradually the organization that had been created to mediate between the CIA and the Air Force had become an institution in its own right. It was now creating its own satellites. Burrows states that disputes between the CIA and Air Force faded as members of both organizations have were able to make their entire careers within the NRO, independent of either the CIA or the Air Force.

The next generation satellite was the KH-11, which appeared in 1977 (the KH-10 was the Manned Orbiting Laboratory and was canceled, see Section 10.3.3 p. 327). The KH-11 provided near real-time close look imagery using and new technology: charged coupled devices (CCD’s). In effect, it was a powerful television camera that could relay images to ground controllers almost as they happened. The KH-11 satellite could perform both area surveillance and close look missions. Ironically, this was similar to the method used by the Army, the least successful of the competitors for the reconnaissance mission. The KH-11 is still in use today.

The KH-11 was very expensive, on the order of a billion dollars per satellite. Funding the KH-11 meant cutting back on KH-9 and KH-8 operations. The Air

---

224Burrows, p. 221-225 & 234.
225Richelson, p. 87.
226Richelson, p. 107.
227Burrows, pp. 205, 221, & 227-234.
The Air Force resisted building the KH-11, suggesting an improved version of the KH-8. It persuaded Secretary of Defense Laird to back the improved KH-8 and cancel the KH-11, but the CIA appealed to President Nixon and got the decision reversed. The $2 billion KH-8 improvement program was cancelled and KH-11 program was begun. The CIA had won.

The NRO has gone on to improve these systems. Today, an improved version of the KH-11, the KH-12 performs all visual overhead reconnaissance. It has be joined by the Lacrosse satellite, a radar imaging system that can “see” through clouds, but with lower resolution.

10.4.7 Reconnaissance Satellite Summary

Although data is difficult to come by, we can draw some conclusions from the history of the reconnaissance satellite. First it seems clear that the Air Force has won responsibility for satellite launch and operations. But the decision as to what should be photographed and when are made in high level committees, such as the COMOR. In the area of satellite development, the NRO appears to have emerged as an independent organization, drawing personnel from both the CIA and the Air Force. But in conflicts over development policy, the CIA appears to have the upper hand.

In the area of data interpretation, both the CIA and the Air Force have their own organizations, which make independent evaluations. The Army tried to field reconnaissance satellites of its own in the 1950’s, but it has been out of the satellite reconnaissance business for decades.

It is interesting to note that the Air Force took the lead in reconnaissance satellite development. Although it reacted to Navy initiatives in the 1940’s to develop satellites in general (see Section 10.2.1 p. 288) by the 1950’s they were the only service or agency with a reconnaissance satellite program. While the strategic bomber mission inhibited ICBM development in the Air Force, it pushed reconnaissance satellite development forward.

\[228\] Burrows, pp. 219 & 234.
\[229\] Richelson, pp. 126-128.
This is an important counter-example to Clark’s theory that well funded organizations are not innovative. The Air Force was aggressive and took the initiative in developing reconnaissance satellites. When the U-2 was given to the CIA, it worked on a bucket dropping satellite. When the bucket dropper was given to the CIA, it adopted a new technology: scanning satellites. It refused to abandon it work on scanning satellites when told to do so. When scanning satellites proved to be a bad technology, the Air Force began building its own bucket dropping satellites with a better resolution than the CIA’s system, and earned a permanent place in reconnaissance satellite development. The Air Force was an initiator, fought to defend its programs, and was innovative and flexible in its efforts to remain in the reconnaissance satellite business. The reason seems to be that the CIA was the agency favored by civilians and more importantly, because the Air Force had an institution (strategic bombers) that favored gaining control of satellite reconnaissance.

We’ve seen the Air Force resist ICBM development for institutional reasons, and we’ve seen the Air Force pushing reconnaissance satellite development on behalf of the very same institution. It seems then that Clark’s theory does not explain every case. A more reliable indicator of behavior is the institutional pressures for or against new space technologies.

This case demonstrates that service/agency competition can yield useful results. The Air Force/CIA/Army competition produced complementary bucket dropping systems and weather satellites. It also produced a number of technological failures (multiple generations of scanner systems). Civilian instructions to abandon scanner development were ignored by the Air Force, demonstrating Clark’s claim that DOD structure of the 1950’s and 1960’s gave the services considerable autonomy. Eventually both the Air Force and CIA technologies were superseded by the NRO’s KH-11. Competition between the service and agencies was both good and bad. It produced useful new developments, but also kept bad technologies in development.
10.5 Communications Satellite History

In comparison with other sections of this chapter, the history of military communications satellite development is simple. With the exception of early competition between the Air Force and the Navy, military communications satellite development has been very a cooperative enterprise in the U.S. It seems that any agency, civilian or military, that has something to contribute to military space communications has been welcomed by the services. Early development by the services was overshadowed by work done by commercial operators and NASA. The first military satellite systems were commercial satellites. When military satellites were finally fielded, the Air Force became (and remained) the dominant operator. The Navy has been successful in developing innovative new communications systems, which were eventually turned over to the Air Force to own and operate.

As we saw in Section 10.4 (p. 333), the Navy (specifically the Bureau of Aeronautics) initiated satellite studies in the late 1940's.\textsuperscript{230} The Air Force refused repeated Navy efforts to form a joint satellite project. The Air Force felt that it was lagging behind the Navy, and that developing a satellite project of its own would prove that it was at least the Navy's equal in this area. But the DOD terminated both projects in 1948. As each service developed boosters, it also initiated a communications satellite program. By the late 1950's, all three services had communications satellite research programs under way.\textsuperscript{231}

By then, NASA had also entered the field. NASA was given responsibility for developing passive satellites (those that simply acted as radio reflectors in space), while the DOD's ARPA worked on active satellites (those that received and transmitted radio signals).\textsuperscript{232} The most successful efforts were project Score\textsuperscript{233} and project Courier. These were experimental satellites were developed by the Army's Signal Re-

\textsuperscript{230}Smith, Delbert D. Communication Via Satellite A.W. Sijthoff-Leyden, Boston, 1976, p 26 and Hall, pp. 71 & 85.
\textsuperscript{231}McDougall, p. 338.
\textsuperscript{232}Smith, p. 48.
\textsuperscript{233}The careful reader will remember Project Score ad the Air Force's launch of an entire Atlas booster into orbit. The payload of that Atlas was a transmitter which broadcast a Christmas greeting from President Eisenhower.
search Laboratory and were launched by the Air Force. ARPA began working on a new operational military satellite system, called Advent. But ARPA’s satellites became obsolete when NASA, in cooperation with the Hughes corporation, proposed a newer and lighter satellite system called Syncomm. The DOD saw the obvious advantages on the Syncomm system. In 1961 it encouraged NASA to develop active satellites, a DOD research area. In 1962, Advent was cancelled.

The first operational communications satellite systems were joint NASA/commercial systems. The Kennedy administration set up Comsat, a commercial monopoly to manage satellite communications. The military expected to purchase all its services from Comsat, but Congress felt that this was a government subsidy of an essentially commercial corporation and pressed the DOD to produce its own system. Also Comsat realized that DOD restrictions would make negotiations with other nations more difficult. In 1964, Secretary of Defense McNamara ordered the Air Force to proceed with development of a military satellite communications system. This was the Defense Satellite Communications System (DSCS). The Air Force’s DSCS program has been the core of U.S. military communications ever since. Third generation DSCS satellites are still being launched today.

Thus, the Air Force was selected as the builder and operator of military satellite communications. But the military did and still does use commercial carriers for its communications traffic. By 1971, 62% of DOD traffic was going via commercial satellites. The Air Force has gone on to build three other communications satellite systems. AFSATCOM is a program that piggybacks small transmitters onto other military satellites and is used to communicate with planes in the air, particularly strategic bombers. The latest military communications satellite system, Milstar, is

---

234Smith, p. 49.
235Smith, pp. 84-85.
237Galloway, p. 113.
238Galloway, p. 115.
239This is when a small payload is added to a much larger payload. The AFSATCOM instrument packages were added on to existing satellites and then flew with them into space. This avoids the cost of launching the small payload independently. Satellite launch costs per kilogram decrease with payload mass. Thus it is cheaper to launch two satellites together than individually.
also an Air Force program.

The Navy has also been active in pressing for new communications satellite technologies. The early DSCS satellite antenna requirements were unsuitable for ships at sea. The Navy initiated its own system, the FLTSATCOM system.\(^{240}\) These were relatively small satellites that could communicate with ships at sea. The cost of this program was significant. The Department of Defense (DOD) funding for space communications rose from $62.9 million in FY72 to $192 million in FY73 because of the FLTSATCOM project.\(^{241}\) The Navy was able to secure the funding to make the project a reality. The first of many launches was in February 1978.\(^{242}\) Once the project had been established, the Navy was quite willing to turn it over to the Air Force to maintain and operate. FLTSATCOM and its successor LeaSat are still in use today.

More recently, the Navy has again been innovative in communications satellite technology. Navy efforts with micro-satellites have changed the attitude of the Air Force, forcing them to look at the possibilities micro-satellites provide.\(^{243}\)

Despite occasional Naval participation, military communications satellites have been largely an Air Force mission since 1964. NASA builds its own communications satellites\(^ {244}\) but these are not for military communications. Occasional innovations have been introduced by the Navy, but the Navy has demonstrated a willingness to let the Air Force operate Navy satellite programs once they are established.

I believe this is because the Air Force has a large, established space organization while the Navy does not. To the Navy, satellite operations are an expense that


\(^{241}\)Galloway, p. 115.


\(^{244}\)The most recent and sophisticated NASA satellite is the Tracking Data Relay Satellite System (TDRSS). This is a constellation of large GEO communications satellites which allow controllers to access orbiting NASA spacecraft (like the Space Shuttle) through it's entire orbit. It is used to relay voice, video, and data from the Shuttle in real time during its missions. TDRSS can also be used to download data from any other satellite in Earth orbit.
can be passed over to the Air Force. To the Air Force, increased operations are an opportunity for growth. This seems consistent with Rosen’s theory that a career-making organization is required to sustain new military functions.

10.6 ASAT Development

In the competition for ASAT weapons development in the U.S., only two contenders have emerged: the Army and the Air Force. Both have developed and fielded systems. At one time or another, both have been the dominant service in U.S. ASAT operations. Today, it appears that the Army has the upper hand. But the struggle hasn’t been between the services so much as in trying to maintain funding for any ASAT project. Theoretically, ASAT research funding had been eliminated, but current “Star Wars” BMD programs can be used as ASAT systems.

Research into ASAT technology began even before there were any satellites to attack. All three services conducted research into ASAT designs, each based on the rockets available to that service. The Air Force was the first to test an ASAT, launching a rocket from a B-47 in October of 1959. Both the Army and the Navy tested systems in 1962, but the Navy dropped out of the competition after 1962.

The Army was the first to field an operational system. Based on the Army’s Nike-Zeus Anti-Ballistic Missile (ABM), project MUDFLAP was designed to use nuclear tipped missiles to down low level satellites (350 mi or 550 km). Based on Kwajalein Island, the system was declared operational on August 1st, 1963. The Army used the ASAT mission to support its Nike-Zeus BMD missile, which was then under threat of cancellation. Here we see how the Army’s existing institutional forces reinforced

---

246 Burrows, p. 139.
247 The Navy system was launched from an F-4B Phantom, a precursor of the F-15 based MHV of the 1970’s. See Burrows, p. 141.
248 Stares, pp. 111 & Table 1, Appendix II, p. 261.
249 Hobbs, pp. 85-96. Nike-Zeus was only tested up to 150 na-mi (280 km). The operational date was also a matter open to debate. A higher level or readiness, in which one missile was always ready for launch, was not reached until May 1964. See Stares, p. 119.
250 Stares, pp. 117-118.
its move into the ASAT role.

The Air Force was not idle during this time. It had abandoned the idea of air-launched ASATs in favor of a satellite interceptor (SAINT). SAINT was designed to co-orbit with enemy satellites and observe them at close range. The idea was to determine the function of the satellite. The Air Force made efforts to add a satellite kill mechanism to SAINT to make it into an ASAT; but the added costs and the desire to emphasize the peaceful nature of the U.S. space program kept that portion from being developed.\textsuperscript{251} One drawback to SAINT was that it could be overloaded by launching numerous decoys, each of which would have to be co-orbited by SAINT. SAINT never flew and was eventually canceled in December of 1962.\textsuperscript{252} The Air Force, although interested in ASATs, seemed unwilling to defend SAINT. DOD insisted that all funding come from the Air Force's budget. The Air Force viewed SAINT as a threat to the Blue Gemini program.\textsuperscript{253} When the Air Force was faced with a choice between a manned mission and ASAT, the decision was obvious.

The Air Force was not giving up on the ASAT mission, however. The same year that the Army first tested its ground-based ASAT (1962), the Air Force issued a requirement for a nuclear-tipped ground-based system.\textsuperscript{254} The Air Force used the Thor IRBM's, which were then being de-commissioned from Europe. Based on Johnston Island in the Pacific, the system became operational on June 10th, 1964.\textsuperscript{255}

The Thor IRBM out performed the Army's Nike-Zeus system in terms of maximum altitude and area the missile covered.\textsuperscript{256} The out-classed Army system's readiness was downgraded after 1964, and the decision to remove the system completely was made in 1966. It was felt that any quick reaction capability the Army system provided would also exist within the Army's Safeguard ABM program. In 1972, six years after the Army system was removed, Safeguard was also shut down.\textsuperscript{257} This

\textsuperscript{251}Stares, p. 115.
\textsuperscript{252}Burrows, p. 140.
\textsuperscript{253}Stares, p. 117.
\textsuperscript{254}Burrows, p. 142.
\textsuperscript{255}Stares, p. 123.
\textsuperscript{256}Burrows, p. 142. The Nike-Zeus had a maximum altitude of 550km, the Thor could reach up to 1,300 km. See Hobbs p. 86.
\textsuperscript{257}Stares, p. 120.
was to be the end of Army activity in ASATs until the mid 1980's.

The Air Force had conducted sixteen ASAT tests through 1970. After 1970, the program was gradually starved of funds. Vietnam made space defense a low priority within the Air Force. Russian co-orbiting ASAT testing had begun in 1968, but had stopped in 1971. U.S. leaders felt that the Soviet Union had stopped testing as an offer to halt the arms race in ASAT technology. Originally, ASATs had been conceived as a counter to orbital nuclear weapons. Now that these systems had been outlawed by treaty, nuclear weapons seemed too severe a kill mechanism for an ASAT. Eventually personnel were transferred away from ASAT work, and the time required to launch went from 24 hours to 30 days. The program was eventually shut down in 1975. 258

In 1976 the Soviet Union resumed testing of its ASAT system. In response, in the last year of the Ford administration, a new ASAT system was started under the Air Force. This new ASAT would be based on a hit-to-kill system rather than nuclear weapons. It would be launched from an F-15 and, using a miniature homing vehicle (MHV) about one foot square, destroy the satellite by striking it. 259

The administration had some difficulty getting the Air Force to start the project. This was because the Air Force feared that the money for ASAT would come from existing programs to harden U.S. satellites against ASAT attack. Despite initial Air Force resistance, the civilians managed to get a special project office created to support the ASAT program. 260 The MHV program went forward, and actually conducted tests in the mid 1980's. But Congress banned further testing and then canceled the project, fearing it might push the Soviet Union into resuming tests of its own ASAT system which had stopped in 1982. Five of these weapons remain in storage in a bunker in Dallas today. 261

After the MHV system was canceled, the Army emerged as the coordinator of ASAT research. It has developed a ground-based hit-to-kill system, which it has also

259 Hobbs, pp. 87-89.
260 Stares, pp. 176-177.

349
tested.\textsuperscript{262} But with a recent decline in world tensions and budgets, Army ASAT efforts have also been canceled.

10.6.1 ASAT Summary

Many of the behavior patterns we see in the history of ASAT research echo things we have seen in the booster history. All three services do initial research and tests, and the Navy drops out of the competition first. The Army fields the first system, which causes the Air Force to react with a larger, more powerful system which out-classes the Army one. The Army system is cancelled and the Air Force system survives. The Army takes the initiative, but the Air Force reacts and fields the better system.

Later in the 1970’s, the Air Force resisted introduction of a new ASAT system. The officers are afraid that ASAT funds will come at the expense of other satellite projects, just as the Navy’s officers were afraid that the Polaris funds would come at the expense of existing Navy projects. The Air Force had a satellite organization that was threatened by ASAT development, hence the resistance. Again we see that institutional incentives within the Air Force resisted a new space system. Civilian intervention was required to get the MHV ASAT program moving.

For the Air Force, it seems that manned missions are a higher priority than ASAT missions. It was willing to sacrifice existing ASAT programs if it felt that its manned programs might be threatened, as it did in 1962 when SAINT was canceled in favor of Blue Gemini.

Civilians have always been ambivalent about ASAT systems. ASAT funding has been very episodic. This is because the U.S. has always been more dependent on its space systems than the Soviet Union. Consequently it has always preferred a world with no ASATs to one where ASAT’s exist on both sides. ASAT development has always been restrained, lest it trigger similar developments in the Soviet Union. It was only after the U.S.S.R. resumed ASAT testing in the mid-1970’s that a serious effort to develop an ASAT was begun. Later, policy makers changed their mind and

\textsuperscript{262}This is the Army’s ERIS: Exoatmospheric Reentry-vehicle Interceptor Subsystem. See Aviation Week & Space Technology February 4th, 1991, pp. 22-23.
allowed the system to die, just like all its predecessors.

Both the Army and the Air Force seem willing to take on the ASAT mission, but unwilling to make much effort to retain it. Each time civilian interest in ASATs had declined, both services have been willing to abandon it. Perhaps the on-again off-again behavior of civilians toward ASAT systems has made military officers wary of trusting their careers in such areas. Rosen's theory would indicate that this lack of continuous funding is why there has been little service loyalty to this mission. Now that ballistic missiles are seen as a more immediate threat (thanks to the Gulf War), funding prospects may have changed, leading all three services, and particularly the Army to investigate theater BMD (more on this in Section 10.7).

10.7 The Current Status of Military Space Missions

We can now turn to the current status of the military services in space. Significant downsizing is taking place in the services now that the Cold War has ended. All three major services are looking for new directions and ways to cope with falling budgets.

Certainly the Air Force will always be willing to sign up for any manned mission. Thus, we can expect Air Force funding for the NASP to continue to be strong. We can also expect, in these budget cutting times, that the NASA/Air Force partnership will be strengthened as neither organization has the funding strength to go it alone. If the U.S. populace is suddenly seized by a desire for a manned mission to Mars and is willing the pay for it, one can bet that NASA will be quick to drop the Air Force.

As we noted in Section 2.1 (p. 33), the Air Force is becoming more dependent on satellites and the services they provide. The Air Force is shifting from a forward-based garrison force to a U.S. based expeditionary force. In other words, the Air Force doesn't know where it will fight next. Thus, space assets, which are global in nature, will become more important.

---

263 General Merrill A. McPeak, Air Force Chief of Staff, address to Air Mobility Command, June 1st, 1992, quoted in "Unfurling the New Flags" Air Force Magazine, July 1992, pp. 49.
The Air Force is certainly the dominant service in space, and it is not afraid to brag about it:

The Air Force oversees and operates nine-tenths of all space systems devoted to US military purposes. This goes a long way toward explaining why approximately nine-tenths of all space-experienced military personnel in the entire Department of Defense wear Air Force blue, and why USAF's space budget grows, in absolute and relative terms, every year. Of all the services and NASA too, the Air Force is by far the biggest spender on space. In the current fiscal year, the US space budget stands at $31 billion. The Defense Department's share is $18 billion. The Air Force accounts for about eighty percent of that — roughly $14.5 billion — and for almost half of the NASA-enfolding national total.\(^{264}\)

Perhaps most important, some in the Air Force feel that space is the one area that is immune to shrinkage in the next few years. The number of generals in Space Command will increase as the total number of generals in the Air Force declines. The head of Air Force Space Command will now be a four-star general instead of a three-star. \(^{265}\) The 1990 Air Force Space Command had 8,500 people in uniform;\(^{266}\) today, it has 16,000 people in uniform.\(^{267}\) The Air Force Space Command expects to eventually double in size to 30,000 people.

Even if Space Command does not grow, it has an established place in the Air Force. Space represents 18% of the Air Force budget. According to Secretary of the Air Force Donald Rice, space will continue to command 18% of the shrinking Air Force budget.\(^{268}\) This is not quite as rosy a picture as those in Space Command paint, but is does seem indicative of an established place in Air Force planning.

We can therefore predict that the Air Force will continue to maintain and possibly upgrade its existing space activities. Air Force articles suggest we build new

---

generations of early warning satellites (DSP), and weather satellites (DMSP). Also emphasized are space-based radar and IR surveillance systems to provide global coverage of air and sea forces (the Air Force wants the radar, the Navy wants the cheaper IR sensors).\textsuperscript{269}

In contrast to the Air Force, Army and Navy space activities are less centralized and are combined with other activities. Both the Army and the Navy are making efforts to change this. Until recently, the Navy's Space Command was headed by a Rear Admiral (one-star general equivalent)\textsuperscript{270} and was organizationally distinct from the Director of Space and Electronic Warfare.\textsuperscript{271} Now the Navy is uniting all space functions under a single Space Command, Control, Communication, and Computer Systems Requirements organization, headed by Vice Admiral (three-star general equivalent) James Tuttle.

Army space functions currently remain divided. The 400-man Army Space Command is headed by a colonel. The Army's Strategic Defense Command, with 1,479 people, is headed by a Lt. General (three-star general equivalent) Robert Hammond, who wants to unify all space activities under his command.\textsuperscript{272}

The one mission area where the Air Force is a minor player is BMD. Since the scud attacks of the Gulf War, defense against ballistic missiles has become a priority. Several missile programs now exist to counter this threat. All are controlled by the Army. The largest of the BMD programs is the Theater High Altitude Area Defense (THAAD) which is expected to have a range of 300-400 km.\textsuperscript{273} That makes THAAD an effective LEO ASAT, and therefore of interest to this dissertation. The Army is the dominant service in BMD. The Army is expected to receive about 70% of the Strategic Defense Initiative Organization's funding, the Navy 15%, the Air Force 5%,

\textsuperscript{269}Canan, James W. “Space Gets Down to Earth” Air Force Magazine, August 1990, p. 34.
\textsuperscript{270}Navy rear admirals can be either one or two star equivalents, depending on whether they are “upper half” or “lower half”. This confusion, I believe, was introduced when the Navy stopped using the of rank Commodore.
\textsuperscript{271}U.S. Naval Institute Proceedings Naval Review Issue, 1992, p. 221.
\textsuperscript{272}Opall, Barbara “Army Command Plans Reshuffling” Defense News June 29th to July 5th, 1992, p. 44.
and allies 10%.

The Army currently manages about 45% of SDIO’s budget. So the Army has a dominant role in developing THAAD (an effective ASAT) and doubtless intends to keep it.

The Air Force and the Navy also seem to recognize the potential of THAAD to provide cash, and both services are trying to get in on the program. According to General Mike Loh, head of Air Combat Command, theater missile defense is an Air Force mission. He feels that the solution to the BMD problem is to use a modified Advanced Medium-Range Air-to-Air Missile (AMRAAM) to destroy the enemy ballistic missile as it is launched. In other words, the Air Force wants to use the idea of THAAD to improve a missile it already owns.

The Navy has a similar idea. It wants to modify the radars on its Aegis class cruisers to operate in the 600-800 km range. It will use these radars to guide the THAAD missile currently under development by the Army and SDIO, but if the missile proves unsuitable for Navy use, the Navy intends to build a missile of its own. The Aegis cruisers would provide a floating missile defense for the Fleet and for forces on shore. The Navy too recognizes the potential for THAAD to enhance an existing service program. As Admiral Frank Kelso, chief of naval operations puts it, “In order for the Navy to take full advantage of the opportunity in the relatively new mission area, we must accelerate our efforts.”

Thus, we can expect that an effective ASAT will be created for the purpose of ballistic missile defense. As we have already stated, an ASAT is currently not needed, but might be needed in the future. I expect that the Army will retain control of this program, despite efforts by the Air Force and Navy to develop THAAD’s of their own.

---


10.8 Historical Lessons

We can summarize each of the service’s history in space as follows: the Army initiates, the Navy innovates, and the Air Force is conservative but successful in the long run.

The Air Force is the most established service in military space operations. In fact, the Air Force is the U.S. military in space. If the Air Force suddenly vaporized, the U.S. military space program would consist of a half-funded shuttle program (NASA), some small orphaned communications satellites (the Navy), a half-funded reconnaissance satellite program (the CIA), and some ASAT/BMD research projects (the Army). The Air Force has been a major participant in all aspects of the U.S. military in space and the Air Force had fought to gain control of every space mission. In space, the Air Force has a stable institution which the other services lack. Once a mission is established in the Air Force, the Air Force space organization can maintain and defend it.

But the Air Force has also demonstrated a conservative attitude towards new space projects, especially if it feels that other, existing missions are threatened. While seeking to control space missions, the Air Force has often not pressed forward with development. The best example of this is the ICBM, where the Air Force fought to keep other services from developing rockets, but had to be forced by civilian leadership to accelerate development. It did this because it felt that the ICBM was a threat to its strategic bombing mission. In the mid-1970's the Air Force resisted building an ASAT system, fearing that the money would come from existing satellite defense programs.

There have been times when existing Air Force institutions have pushed it to take the initiative in space. The Air Force was the leader in reconnaissance satellite development before Eisenhower gave the mission to the CIA. But the Air Force's primary interest in space is manned flight, and it will sacrifice any other space program to obtain it. Unfortunately for the Air Force, manned space flight is of little military value. The Air Force has come close to manned flight many times, but each time events or politics have prevented it. The lesson here is that the Air Force is good a
maintaining existing space systems, but in most cases its existing space institutions prevent it from taking the lead in new space technologies.

Army and Navy efforts in space, either through civilian intervention or because of cultural bias, have been episodic. They have not developed the institutional stability in space that the Air Force has. They have a history of developing new technologies which the Air Force seems to overlook. A factor which has pushed the Air Force to innovate is competition from other services who often seem to be ahead of the Air Force in space research. Here are some examples: The Air Force responded to Army liquid fuel rocket development with no less than three separate liquid missile programs of its own. The Air Force responded to the Navy’s solid fuelled Polaris with a solid fuelled missile of its own (Minuteman). The Air Force’s nuclear-tipped ground-based ASAT program came after the Army’s. This reactive strategy has worked well for the Air Force against the Army. The Air Force retained all three of its liquid fuelled rockets, while the Jupiter disappeared. Air Force ASAT technology proved to be superior to the Army’s in the long run and so the Air Force’s ASAT out-lived the Army’s by several years.

The Navy was an early player in the rocket development contest in order to get into strategic bombardment. Since then, its interest in space had been primarily based on how it can serve the fleet. When the Navy feels a space project is of some benefit—either in expanding the Navy’s mission or helping the fleet perform its missions—then it has demonstrated an impressive ability to fund innovative space projects. An example of mission expansion is the Polaris submarine-based ballistic missile project. Polaris served as a means of getting the Navy a ballistic missile role. Several other space projects have been initiated by the Navy to serve the fleet. The Transit and GPS navigation systems were Navy initiatives. When the DSCS communications satellite proved unsuitable for small ships at sea, the Navy initiated, funded, and built its own communications satellite, the FleetSatCom. FleetSatCom’s flexibility eventually proved useful to all military services.278

But the Navy had not felt a need to retain control of space projects once they are in place. GPS and all communications satellites are now launched, manned, and maintained by the Air Force. As one Admiral joked, "Our idea of a joint program is one the Air Force pays for and the Navy uses."\(^{279}\) Thus, the Navy can be a powerful innovator and spur to the Air Force to adopt a new space technology, provided the technology serves the fleet in some way. The Navy is not interested in controlling space operations. Instead it prefers to hand over facilities to the Air Force.

The Army has often been an initiator in space. It has an impressive series of U.S. military space firsts to its credit. It fought hard to retain its rocket capability, refusing at one point to give up Doctor von Braun to NASA. Since then, Army space activities have centered on BMD and ASAT roles. The Army space programs have suffered from erratic funding and Air Force successes in gaining control of space missions. At times, there has been no Army space program at all. Still, we can assume that the Army will accept any space mission given to it and \(\text{will}\) take the lead in applying new technologies. This is because any space mission is viewed by the Army as an additional mission area. It does not have a well established space organization that might be threatened by new ways of doing things in space. Thus, the Army and the Navy are alternatives to the Air Force in space. Both the Army and the Navy have played innovator roles in the history of military space missions.

Competition between services over space projects appears to be an inherent part of the DOD of the 1940's, 50's, and 60's. We have seen several cases where civilian efforts at centralization were thwarted by continued service research and development (as predicted by Clark, Lucas and Dawson). The potential rewards of these research projects are so great that services have been willing to ignore orders and to pursue them.

Competition produces both good and bad results. Often, the innovations of "loser" services (usually the Army or Navy) have prodded the winning service (usually the Air Force) to greater efforts in new areas. Competition has also produced bad technologies

---

(like the scanning reconnaissance satellite) and redundant systems (like the Thor and Jupiter missiles). Although occasionally wasteful, competition does provide benefits. It pushes new technologies and systems and prods "status quo" services into new activities. In practice, this has meant encouraging the Army and Navy to develop new space technologies, that moved the more conservative Air Force to action.

But competition between the services is less prevalent today than it was during the 1940's or 1950's. This is because service autonomy has been dramatically reduced since then. In the mid 1950's, Congressional oversight of the military was quite limited by modern standards. In 1959 the Russel Amendment allowed the Congress to begin line itemization of the defense budget. Congressional involvement in the military budgeting process has grown steadily since, with more committees with divided and overlapping responsibilities, more congressmen involved in the process, more amendments, and a longer budgeting process. This expansion of Congressional activity increased dramatically during the reforms of the 1970's.\textsuperscript{280}

In addition, the power of the Secretary of Defense over the services has also increased. Beginning with the Defense Re-Organization Act of 1958, and then with the tenure of Bob McNamara, Secretary of Defense (SecDef) under Kennedy and Johnson, the power of this office over the services dramatically increased. Although few SecDef's after McNamara have exercised as much power, the influence of the SecDef has remained permanently expanded.\textsuperscript{281}

Finally, the power of joint commanders has been increased, most dramatically by the Goldwater-Nichols Act of 1986. The Chairman of the Joint Chiefs of Staff (CJCS), has been elevated to the chief military advisor to the President and SecDef. The unified commanders have also been given greater powers over the units they command, making them less dependent on the services that provide those units.\textsuperscript{282}

Thus, over time, the ability of the services to engage in inter-service rivalry has been challenged by reduced autonomy and increased civilian micro-management. This

\textsuperscript{280}Lindsay, pp. 371-400.
\textsuperscript{282}Hendrickson, pp. 105-114.
has produced another effect: service log rolling. That is, when faced with a more interventionist Congress and more importantly, a more powerful SecDef, the services have reacted by establishing treaties with one another in order to present a unified front to the SecDef.²⁸³

The services no longer behave in the same competitive fashion as they did in the 1950's. Whether or not this behavior will continue in the future is unclear. It is possible that with an shrinking defense budget, the patterns of cooperation will break down and the services will be openly critical of each other once again. Or, perhaps they will maintain their cooperative behavior, believing that it is the best way to defend the defense budget against cuts. The point is that inter-service competition is no longer a given. Simply allowing the services to expand into new space missions may not be enough. It may require civilian intervention to create competition, to recreate incentives to innovate, and to tolerate parallel programs.

We can also make some statements about military space projects in general. In this history, we have seen many booster research programs cancelled when it came time to build a prototype. Prototype rockets cannot be built with limited funds. Strong civilian support is usually required to begin initial hardware construction. This is not to say that space launchers require strong civilian support, but rather that it is less likely that a project will succeed without strong civilian support.

Brown claims that concurrent strategic bomber production offered a lot of political advantages to the Air Force over slower, more careful methods of bomber production.²⁸⁴ Space systems are an extreme case of concurrent production: there is almost always a very small production run. The prototype is often a substantial portion of the production run. Because much of the money is required up front to build a prototype, this seems to make space launchers more difficult to fund than other large military systems.

There are technological enthusiasts within each service who want to develop mili-

tary space projects. Examples of these are the NRL and the Von Braun rocket team. If an established group within the service is opposed to the space project (and they often are), a sub-service pro-space group will usually only succeed if civilians or senior officers create an independent organization with a separate channel of funding. Examples of these are the Army Ballistic Missile Agency, the Western Development Division, the Special Projects Office, and NASA.

Later on in the life of a space project, civilian interest often declines. At this point, without service support, the project will often die. Examples include the Air Force cancellation of the ICBM project in the late 1940's, and the Army and Air Force termination of the ASAT programs of the 1960's and 1970's.\textsuperscript{285} Without a supporting organization within a service, the long term prospects for a military space project are dim. If a project is to be sustained, it must have an organization which will own it, identify with it, and fight for it.

10.9 Policy Recommendations

Now we want to apply these lessons to the policy recommendations outlined in Chapter 1 (p. 20). The recommendations are categorized by threat level one through five and can be divided into two broad categories: The lowest level threat policy recommendations are incremental improvements of existing systems (nuclear hardness, anti-jamming, impact detectors, decoys). As the threats increased, the recommendations become more radical and more expensive.

First, we look at how to best implement incremental improvements of existing systems. Existing institutions are the best choice for incremental improvements. These organizations will have natural a bias toward improving and increasing the number of systems that they operate.

When it comes to improvements in existing communications and navigation sys-

\textsuperscript{285} This trend is neither good or bad. Good projects have been maintained by strong service interest (communications and reconnaissance satellites) while useless programs have been preserved (the Air Force's X-20 project). On the other hand, good projects have died because of lack of service interest (the ICBM).
tems, the Air Force is the obvious candidate. They are the only service with a well established space organization. Consistent with Clark’s theory, the Air Force’s Space Command talks about improving existing systems, not about new systems.

The NRO is the obvious choice for incremental improvements to reconnaissance systems. They too are a well established organization (a CIA/Air Force hybrid), and will probably be quite happy to provide improvements to existing Lacrosse and KH-12 satellites.

One of my recommendations is to retain reconnaissance aircraft as a backup for reconnaissance satellites. The Air Force will probably be glad to add this to its list of justifications for reconnaissance aircraft. However, it may also suggest the Shuttle as a backup. Although the Shuttle is capable of performing such a mission,\textsuperscript{286} using the Shuttle in wartime would be risky and costly. Even though the Shuttle is more maneuverable than a reconnaissance satellite, it could also be destroyed by KKV ASATs. The launch costs for a single week-long Shuttle mission runs into the hundreds of millions of dollars, and would would rival the cost of a new reconnaissance satellite that could remain in orbit for a decade. The Air Force should be prevented from using the Shuttle as a wartime backup reconnaissance platform. In general, civilian policy makers should oppose of Air Force efforts to procure manned military space systems. There is no justification for manned military space systems.

Next we examine how to best implement new space systems, should the become necessary. Existing institutions are unlikely to embrace micro-satellites and space gun launchers because they threaten existing space systems. When it comes to more radical space systems, we can use the forces of competition to our advantage. In space, the Army and Navy are outsider services, without well established space organizations (although the Navy is trying). They will be more willing to consider innovative solutions to problems.

In the area of micro-satellite development and construction, both the Army and the Navy are likely to develop systems more rapidly and to prod the Air Force to

\textsuperscript{286}The Shuttle is capable of making a single orbit reconnaissance flight and returning to its original base.
follow suit. The Navy in particular has a history of developing innovative communication satellites. In fact, recent Navy research efforts have pushed the Air Force into initiating a micro-satellite research program of their own: "Though DARPA and the Navy have taken the lead, USAF also is at work on small satellites. This marks a shift in position for the Air Force, which until very recently questioned the cost-effectiveness of what it called 'cheapsats'."²⁸⁷ As we might expect, the Air Force took a conservative attitude toward micro-satellites, seeing them as a threat to the already established larger communications satellite programs. But the Navy, which saw a chance of getting dedicated local communication services, started looking into them. Threatened by the idea that the Navy might develop micro-satellites on its own, the Air Force has now begun to move forward. This is a familiar pattern. Giving the project directly to the Air Force without competition is likely to produce a conservative, slow program which might never produce a useful prototype.

Innovation is also required in space gun development. Both the Air Force and NASA are unlikely to push this technology for two reasons: First, unlike rockets, space guns are inherently an unmanned launch system because no human could survive the violent acceleration of launch. Both NASA and the Air Force have a strong bias toward manned systems. The only launch system they have successfully fielded since the 1960's is the Space Shuttle. They have been unwilling to build a new unmanned launcher since. Second, both NASA and the Air Force have substantial organizational investments in rocket technology and in large satellite. A space gun launching micro-satellites would be a threat to those systems.

Space guns will also encounter another difficulty: cost. The fact that all the expendable boosters in use today are derivatives of 1950's rockets means that it is very hard to fund a completely new launch system (see Section 9.5.2, p. 263). NASA and the Air Force are unlikely to fund a $7 billion space gun which threatens their rocket establishment and is a dead end as far as manned flight is concerned. The Army of the Navy are much more likely to be able to display the initiative and flexibility

required to build a space gun. Launching objects into orbit would be a new mission area for both the Army and the Navy. Also, the Army and the Navy have no existing launcher or satellite development institutions to be threatened. The Army is more likely to try and retain a space gun within the Army, while the Navy would probably be willing to turn it over to the Air Force.

If it becomes necessary to deploy KKV ASATs, I recommend that we open the field to all the services. Almost certainly, both the Air Force and the Army would compete for the mission. Both services have a history in ASAT deployments. Both services have developed or are developing KKV ASATs. My guess is that the Army will be more successful. This is because the Air Force's existing institutions have resisted ASAT missions in the past (as with the MHV ASAT in the 1970's). The Army, on the other hand, has a history of using the ASAT mission to support is BMD missiles (as with the Nike-Zeus BMD in the 1960's). The existing institutions within the Army would favor acquiring an ASAT role to bolster its existing dominance in the BMD area. The Air Force and the Navy will probably be interested in the ASAT mission only to the extent that it can be used to justify more Aegis cruisers or more AAMRAM missiles on F-15 fighters.

As we noted in Section 10.8 p. 355, inter-service competition may not happen spontaneously. Civilians may have to tolerate, or even create duplicate programs to create a competition.

Finally, it seems unlikely that we will be able to halt further ASAT research. In our recommendations, we noted that the U.S. already has more than sufficient offensive space technology. Currently, Ballistic Missile Defense (BMD) and Theater High Altitude Air Defense (THAAD) are dynamic research areas that will also yield new ASAT systems. All three services are competing for this mission. We can expect the services to develop BMD and ASAT systems. Perhaps more significantly, BMD is being developed for reasons other than as an ASAT. Until perceived BMD needs recede, these programs are likely to continue. Pointing out the lack of need for ASAT

---

[288] The Air Force still has its MHV systems in storage. The Army has tested several KKV's as BMD systems and is continuing to develop new ones.
systems is not sufficient to halt BMD development.

I claim that the existing Air Force dominated space organizational structure is sufficient for incremental improvements required today. In the future, however, more radical solutions to space threats may be required. These needs will be better served by more an open and less centralized structure with competition between services.
Appendix A

Soviet ASAT Kill Radius Calculation

Introduction

The Soviet system uses a set of pellets that are scattered by an explosion just prior to intercept. The high closing velocity ensures that the pellets have enough kinetic energy to destroy the satellite. The U.S.A.F. claims that the kill radius was 1 km, and later upped their estimate to 8 km. ¹ I claim that the kill radius must be substantially less than 1 km.

How Much Mass is Needed to Kill a Satellite?

I will assume that the pellets are accelerated to a 3 km/sec closing velocity by explosives as the ASAT closes with its target. From Chapter 5 we know that a pellet closing at 3 km/sec can destroy a satellite 180 times its mass (See Equation 5.1, p. 158).

Satellite Area Density

Using survey data, I also know the mass of satellites based on their cross sectional area.\(^2\) The data plots out to the following equation:

$$\text{Mass} = 62 \times 10^3 \times \text{Area}^{1.13}$$

Where Mass is the mass of the satellite and Area is the cross sectional area. Thus, a satellite with a cross-sectional area of 1 sq-m has a cross sectional mass density of 62 kg/sq-m. For an area of 100 sq-m, it's 112 kg/sq-m. For an area of 10 sq-m, it's 83 kg/sq-m. And for a 0.10 sq-m satellite, it's 46 kg/sq-m. Since a typical satellite is in the 1 to 10 sq-m range, we'll use 73 kg/sq-m.

Mass Requirements for Small Pellets

If the impacting pellets are 1/180th of the mass of the target satellite the satellitewill be destroyed. If the average density of a satellite is 73 kg/sq-m, then the pellets need to have a density of $73/180 = .406$ kg/sq-m to destroy the target satellite.

Destructive Radius

The Soviet ASAT has a total mass of 2500 kg.\(^3\) Assuming all of this mass is accelerated and uniformly distributed over a circular cross sectional area by the explosion (rocket motors, guidance, and sensors as well), how big an area could I cover to 0.406 kg/sq-m? $2500/0.406 \cong 6,158$ sq-m. Using $\text{Area} = \pi \times \text{Radius}^2$ I can calculate the kill radius is 44 m, or 0.044 km. Even under the best of assumptions, the earlier conservative Air Force estimate appears to be off by a factor of 180.

---

Appendix B

Brilliant Pebbles Calculation

Pebble Kill Radius

The lastest brilliant pebbles test vehicle was fired for 14 sec continuously with thrust “up to” 4 G’s.\(^1\) Since the vehicle was unsupported, the min thrust was, presumably, 1 G.

Taking the max possible $\Delta V$ of $10m/s \times 4G's \times 14sec = 560m/sec$. Assuming ICBM’s take 10 minutes to reach the pebble’s operational altitude, the pebble would have 600 sec to intercept. $600sec \times 560m/sec = 336000m$ or 336 km. Thus, ignoring the 14 sec acceleration time, each pebble has an interception window of a circle with a 336 km radius.

Single Orbit Absentee Rate

Assuming an operational altitude of 500 km in a circular orbit, the orbit circumference would be $(6370km + 500km) \times 2 \times \pi = 43,165km$. If I populated this orbit with pebbles, each of which could cover $336km \times 2 = 672km$, then it would require $43,165km/672 \approx 64$ pebbles to cover the entire orbit. Thus the “absentee rate” is 64. That is, for every pebble in position to kill a Soviet missile, 63 others are out of position.

\(^1\)Aviation Week & Space Technology, August 13th, 1990, p. 73.
Orbital Absentee Rate

Note that these "disks" which represent the pebble's kill zone are just touching as I fill this orbit. Thus only one great circle line is actually covered. But I in fact have to cover all the Soviet missile fields with these disks, 24 hours a day. Assuming I place the pebbles in 90 degree inclined orbits, how many pebbles are required to cover the fields?

Because the earth rotates beneath satellite orbits, coverage of all area north of 45 degrees latitude is required to be assured coverage of all the targets. I am assuming that all ICBM fields lie north of 45 degree latitude, what is the circumference of a line drawn at 45 degrees latitude? $\frac{R_{Earth} \times 2\pi}{\sqrt{2}} = 28,301 km$. This is not a needed figure because the absentee rate depends on what fraction of the latitude the targets are spread out over.

Soviet missiles appear to be spread out over 75 degrees longitude. Since the pebble orbits would cover territory both north-bound and south-bound, the coverage is doubled. I can think of it as only having to cover 180 degrees of latitude. $\frac{75}{180} = .41666$ Thus an additional 2.4 absentee rate is introduced. For every orbit over Soviet ICBM fields, 1.4 orbits are elsewhere in the globe.

Total absentee rate is then $64 \times 2.4 \approx 154$.

Factors not Accounted for

This figure is probably very low as I have made some very generous assumptions. First, the pebble orbits would have to be packed tighter together because the disks just touch. This leave a lot of space uncovered between them which must be covered by other adjacent orbits. Inevitably this will lead to some overlap. This might be partially overcome by using inclinations of less than 90 digress, but again I believe that substantial overlap will occur.

Also, the density of missiles latitudinally across the Soviet Union must vary. Consequently, the defender must place a sufficient number of pebbles in each station to handle the densest area of the Soviet Union. This, in turn is partially offset by the fact that silos are not lined up east to west. Certain "out of position" pebbles will be
able to attack northern missiles.

Still, I feel that assumption that each in position pebble can attack a launched ICBM is a generous one.

Launch Costs

Current Space Shuttle costs are $6000 to $10,000 per lb.² Titan costs, with a large number of purchases, have fallen from $3,000/lb. to $2,000/lb.³ The pebbles are supposed to weigh 20lb. As a launch cost of $2000/lb, each pebble would cost 20lb × $2000 × 154 = $6.16million per pebble-attack, just for launch costs. If the dreams of the coil gun builders are realized and launch costs fall to $300/lb., the launch costs fall to $924 thousand per pebble-attack.

But this pales in comparison to the projected item costs. Pebbles are expected to cost $1.1 to $1.4 million per interceptor.⁴ With an absentee rate of 154, each pebble-attack comes to 154 × $1.1million = $169.4million. I believe this far exceed the cost of even the larges missiles in the Soviet Inventory, no matter what accounting system is used.

---

³ *Aviation Week & Space Technology*, March 19th, 1990, p. 188.
Appendix C

Orbital Simulation Code

#include <stdio.h>
#include <math.h>

main()
{
  int t, dt, tt;
  float x, y, vx, vy, r, fg, dvx, dvy;

  fprintf(stderr, "Input x, y, vx, vy, display frequency, total time:\n");
  while (scanf(" %f %f %f %f %f %d", &x, &y, &vx, &vy, &dt, &tt) != 6)
    fprintf(stderr, "Invalid format, try again.\n")
  printf(
    "\n    X    Y    Radius    Vx    Vy    Fg    t mins    hrs\n"),
    x = x + vx * 0.5;  /* Compensate for initial under/over estimation. */
    y = y + vy * 0.5;
    for(t = 0; t <= tt; t++)
      {
        r = sqrt(pow(x, 2.0) + pow(y, 2.0));
        fg = 3.9871 * pow(10.0, 5.0) / pow(r, 2.0);
        dvx = fg * x / r;
}
dvy = fg * y / r;

if(t % dt == 0)
    printf(" %8.0f %8.0f %9.0f %9.3f %9.3f %6.3f %5d %5.1f %5.2f\n",
        x, y, r, vx, vy, (fg * pow(10.0, 3.0)), t, (t / 60.0), (t / 3600.0));

x = x + vx;

y = y + vy;

vx = vx - dvx;

vy = vy - dvy;

}
Appendix D

Space Gun Launch Simulation

Code

#include <stdio.h>
#include <math.h>

main()
{
    float density();

    int t, dt, tt;
    float x, y, vx, vy, v, r, fg, dvx, dvy, fdrag;

    fprintf(stderr, "Input x, y, vx, vy, display frequency, total time:\n");
    while (scanf(" %f %f %f %f %d %d", &x, &y, &vx, &vy, &dt, &tt) != 6)
        fprintf(stderr, "Invalid format, try again.:\n");

    printf("\n X  Y  Radius  Vx  Vy  V  Fg  Fd  t  mins  hrs\n");
\[ x = x + vx \times 0.5; \quad /* \text{Compensate for initial under/over estimation.} */ \]
\[ y = y + vy \times 0.5; \]

for (t = 0; t <= tt; t++)
{
    r = sqrt(pow(x, 2.0) + pow(y, 2.0));
    v = sqrt(pow(vx, 2.0) + pow(vy, 2.0));
    fg = 3.9871 \times pow(10.0, 5.0) / pow(r, 2.0);
    dvx = fg \times x / r;
    dvy = fg \times y / r;

    fdrag = -0.50 \times 0.14 \times 1.29 \times \text{density}(r) \times 0.51 \times
    \frac{pow(v, 2.0) \times 1000.0}{1300.0};

dvx = dvx - fdrag \times vx / v;
    dvy = dvy - fdrag \times vy / v;

    if (t \% dt == 0)
        printf("%6.0f %6.0f %6.0f %6.3f %6.3f %6.3f %6.3f %5d %5.1f %5.2f\n",
            x, y, r, vx, vy, v,
            (fg \times pow(10.0, 3.0)), fdrag,
            t, (t / 60.0), (t / 3600.0));
    x = x + vx;
    y = y + vy;
    vx = vx - dvx;
    vy = vy - dvy;
    if (r < 6378)
        {
            printf("Impact!\n");
            exit(0);
float density(alt)
float alt;
{
    if((alt - 6378) <= 0.305) return(0.96); /* Less than 1000 ft. */
    if((alt - 6378) <= 0.611) return(0.93); /* Less than 2000 ft. */
    if((alt - 6378) <= 0.916) return(0.90); /* Less than 3000 ft. */
    if((alt - 6378) <= 1.22) return(0.86); /* Less than 4000 ft. */
    if((alt - 6378) <= 1.53) return(0.83); /* Less than 5000 ft. */
    if((alt - 6378) <= 3.05) return(0.69); /* Less than 10,000 ft. */
    if((alt - 6378) <= 4.58) return(0.56); /* Less than 15,000 ft. */
    if((alt - 6378) <= 6.11) return(0.46); /* Less than 20,000 ft. */
    if((alt - 6378) <= 7.64) return(0.37); /* Less than 25,000 ft. */
    if((alt - 6378) <= 9.16) return(0.30); /* Less than 30,000 ft. */
    if((alt - 6378) <= 10.7) return(0.24); /* Less than 35,000 ft. */
    if((alt - 6378) <= 12.2) return(0.19); /* Less than 40,000 ft. */
    if((alt - 6378) <= 13.7) return(0.15); /* Less than 45,000 ft. */
    if((alt - 6378) <= 15.3) return(0.12); /* Less than 50,000 ft. */
    if((alt - 6378) <= 16.8) return(0.091); /* Less than 55,000 ft. */
    if((alt - 6378) <= 18.3) return(0.071); /* Less than 60,000 ft. */
    if((alt - 6378) <= 19.9) return(0.056); /* Less than 65,000 ft. */
    if((alt - 6378) <= 21.4) return(0.044); /* Less than 70,000 ft. */
    if((alt - 6378) <= 22.9) return(0.035); /* Less than 75,000 ft. */
    if((alt - 6378) <= 24.4) return(0.028); /* Less than 80,000 ft. */
    if((alt - 6378) <= 26.0) return(0.022); /* Less than 85,000 ft. */
    if((alt - 6378) <= 27.5) return(0.017); /* Less than 90,000 ft. */
if((alt - 6378) <= 29.0) return(0.014); /* Less than 95,000 ft. */
if((alt - 6378) <= 30.5) return(0.011); /* Less than 100,000 ft. */
if((alt - 6378) <= 33.6) return(0.007); /* Less than 110,000 ft. */
return(0.0);