A Framework of Methods and Process Improvements to Better Align Technology Development with DoD Space Enterprise Priorities

by

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ABSTRACT

Strong research and development planning is critical to ensuring the necessary technologies have been matured for future acquisition programs. For the DoD Space Enterprise, research and development occur across a myriad of government laboratories, Federally Funded Research & Development Centers, other government agencies, academia, and industry. This work is governed through many different processes, but improvements could be made to the communication, collaboration, cooperation, and coordination through a well aligned governance structure.

The use of Model-Based Systems Engineering, Technology Roadmapping, and Design Structure Matrices can transition the DoD to an approach that documents the capability needs, priorities, timelines, and system interdependencies in a way that facilitates knowledge sharing and cooperative, coordinated system planning.

This process would begin by developing a solution-neutral functional architecture and decomposing the technology needs against the planned future acquisition timelines in a technology roadmap that integrates all space mission areas. A streamlined process with distinct functions, each chaired by a single enterprise authority, executed by a space community chief architect, and with participation by the relevant stakeholders, can lead to a portfolio management process that aligns technology development with enterprise priorities. The integrated roadmap can be used to communicate transparently with all R&D entities so that investment decisions can be aligned with the future acquisition needs. This approach will take best advantage of the incredible research that is occurring throughout the country for space systems, and ensure that the right technology is being shepherded for on-orbit demonstration at the right time.

Thesis Supervisor: Pat Hale
Title: Director, System Design and Management Fellows Program

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I also have to thank all of the MBSE expertise at SMC that shared their work in the field, and provided a sounding board for my thoughts. Your examples, lessons learned, and insights were incredibly valuable in helping me identify when the use of MBSE is practical and feasible, and when it may not be.

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1.4 Acronyms

AEHF	Advanced Extremely High Frequency
AFMC	Air Force Material Command
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AFSPC/CA	AFSPC Chief Architect
AIAA	American Institute of Aeronautics and Astronautics
ALASA	Airborne Launch Assist Space Access
AMC	Army Material Command
AoA	Analysis of Alternatives
APL	auxiliary payload
ARL	Army Research Laboratory
ARLTAB	Army Research Laboratory Technical Assessment Board
ASD(R&E)	Assistant Secretary of Defense for Research and Engineering
ATC	Applied Technology Councils
ATD	Advanced Technology Demonstrations
BAA	Broad Agency Announcement
BBP	Better Buying Power
CAPE	Cost Assessment and Program Evaluation
CBA	Capabilities-Based Assessment
CCT	Capability Collaboration Team
CDD	Capability Development Document
CFLI	Core Function Lead Integrator
CFSP	Core Function Support Plan
CGA	Capability Gap Assessment
CIO	Chief Information Office
CNA	capabilities needs assessment
COI	Community of Interest
CONOP	concept of operation
CRADA	Cooperative R&D Agreement
DAB	Defense Acquisition Board
DARPA	Defense Advanced Research Projects Agency
DAS	Defense Acquisition System
DCS	Defensive Counterspace
DEPSECDEF	Deputy Secretary of Defense
DHS	Department of Homeland Security
DMAG	Deputy's Management Action Group
DoD	Department of Defense
DoDAF	DoD Architecture Framework
DoDI	DoD Instruction
DoE	Department of Energy

DSC	Defense Space Council
DSM	Design Structure Matrix
DTC	Directorate Technology Council
DTIC	Defense Technical Information Center
EC	Enabling Capability
ExCom	Executive Committee
FCC	Flagship Capability Concepts
FFRDC	Federally Funded R&D Centers
FNC	Future Naval Capabilities
FY	fiscal year
FYDP	Fiscal Year Development Plan
GAO	United States Government Accountability Office
ICD	Initial Capabilities Document
ICD	Interface Control Document
INCOSE	International Council on Systems Engineering
IPT	Integrated Product Team
IR&D or IRAD	Independent Research and Development
IRB	Investment Balance Reviews
JAC	Joint Advisory Committee
JCIDS	Joint Capabilities Integration and Development System
JCTD	Joint Capability Technology Demonstration
JICSPoC	Joint interagency combined space operations center
JPL	Jet Propulsion Laboratory
JROC	Joint Requirements Oversight Council
KPP	Key Performance Parameter
KSA	Key System Attribute
LRRDPP	Long Range Research and Development Program Plan
MAJCOM	Major Command
MBSE	Model-Based Systems Engineering
MDA	Milestone Decision Authority
MDD	Material Development Decision
MEMS	microelectromechanical systems
MILSATCOM	Military Satellite Communications Directorate
MIT LL	Massachusetts Institute of Technology Lincoln Laboratory
MOO	multi-objective optimization
MSA	Material Solution Analysis
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSS	National Security Space

OCS	Offensive Counterspace
OMG	Object Management Group
ONR	Office of Naval Research
OPIR	Overhead Persistent Infrared
ORS	Operationally Responsive Space
OSD	Office of the Secretary of Defense
PAP	pre-acquisition process
PDSA	Principal DoD Space Advisor
PMG	Portfolio Management Group
PoR	Program of Record
PPBE	Planning, Programming, Budgeting and Execution
R&D	Research and Development
RCO	Rapid Capabilities Office
RDECOM	Army Research, Development, and Engineering Command
RIF	Rapid Innovation Fund
RQ	Aerospace Systems Directorate (AFRL)
RSGS	Robotic Servicing of Geostationary Satellites
RV	Space Vehicles Directorate (AFRL)
RWG	Roadmap Working Group
S&T	Science and Technology
SAB	Scientific Advisory Board
SAF/AQS	Office of the Assistant Secretary for Acquisition, Space Programs
SBEM	Space-Based Environment Monitoring
SBIR	Small Business Innovation Research
SBIRS	Space-Based Infrared System
SE	Systems Engineering
SECAF	Secretary of the Air Force
SECDEF	Secretary of Defense
SERB	Space Experiments Review Board
SERB	Space Experiments Review Board
SMC	Space and Missile System Center
SMC/AD	Advanced Systems and Development Directorate
SMC/SY	Space Superiority Systems Directorate
SME	subject matter expert
SMI	Space Modernization Initiative
SPO	system program office
SSA	Space Situational Awareness
SSC	Space and Naval Warfare Systems Centers
STP	Space Test Program
STTR	Small Business Technology Transfer
SysML	Systems Modeling Language
TOG	Technology Oversight Group
TRA	Technology Readiness Assessment

TRB	Technology Review Board
TRD	Technical Requirements Document
TRL	Technology Readiness Level
UML	Unified Modeling Language
UNP	University Nanosat Program
URI	University Research Initiative
USD(AT&L)	Under Secretary of Defense for Acquisition, Technology and Logistics
USNORTHCOM	United States Northern Command
USSTRATCOM	U.S. Strategic Command
VCJCS	Vice Chairman of the Joint Chiefs of Staff
XS-1	Experimental Spaceplane One

Chapter 2 Introduction

2.1 Motivation

A revelation is happening in the United States, where the general public, Congress, and the White House are beginning to accept that the relative sanctuary experienced in the space domain over the recent decades may not remain free of hostile action. With this shift in perception has come a momentum to change the way we think about space as warfighters, as acquirers, and as researchers.

With the growing budget pressures since the Cold War, and tremendous budget pressures since the Budget Control Act of 2011, there has also been an increasing drive to do things more smartly, find ways to use our existing capabilities more creatively, and think more innovatively. Frank Kendall, Under Secretary of Defense for Acquisition, Technology, and Logistics, has issued three iterations of his Better Buying Power (BBP) initiatives, aimed at guiding the workforce and industry toward smarter decision making and more effective acquisitions. In one of his recent implementation directives, he highlights,

> New in Better Buying Power 3.0 is a stronger emphasis on innovation, technical excellence, and the quality of our products. The technological superiority of the United States is now being challenged by potential adversaries in ways not seen since the Cold War. Efficiency and productivity are always important, but the military capability that we provide to our warfighters is paramount. [1]

The BBP 3.0 initiative, in addition to his previous memorandum titled, "Long Range Research and Development Program Plan (LRRDPP) Direction and Tasking," highlight the need to be better than we currently are at planning our emerging technologies and developing military advantage for ourselves in the future. [2]

In the space domain, we are playing catch-up in this area, where we have neglected Research and Development (R&D) funding and deliberate technology maturation planning in lieu of continued builds of existing constellations and technology, and paying for cost overruns on existing acquisitions. [3] Additionally, we are now recognizing the need for increased space situational awareness, space control, and space protection capabilities that have not received adequate attention in our historical acquisition plans, which prompted Gen John Hyten, the Commander of Air Force Space Command, to release a new Commander's Strategic Intent and subsequent Space Enterprise Vision. These documents capture the need to think different about the space domain, and be prepared to "protect and defend our space capabilities as we do in all other domains."

Gen Hyten's first objective outlined in his Commander's Strategic Intent is,

> We will pursue space acquisition strategies to leverage mature technology and develop replenishment concepts to introduce smaller, less complex systems that consider life-cycle costs from the outset. Our space modernization efforts are critical to reducing technology risk and enabling low-risk development and production. [4]

I began this thesis as an answer to Mr. Kendall's and Gen Hyten's calls for more forward thinking, and out of personal desire to develop an actionable plan for improving some aspect of our Department of Defense (DoD) Space Enterprise. I wanted to focus on the decision making processes for the research and development of future space technology, because I did not believe that we are well organized and taking full advantage of the tremendous research and engineering that is occurring around the country.

This thesis began with no preconceived solutions, but a desire to trace the paths from initial funding to technology insertion into the program offices. I believe that with the advancement of systems engineering as a discipline, we need to be incorporating more systems thinking and tools into our decision making at all levels. In fact, if we can find a way to make our needs more transparent, our reviews more data-driven, and our decisions more consistent, we can harness the technology that is being developed and plan for future research, ultimately resulting in incredible advancements across all aspects of the space-domain.

2.2 Introduction

Throughout the decades, funding of the Department of Defense has risen and fallen like tidal waves, increased by the threat and reality of war, and waning with the success and exhaustion of war's completion. The United States' ability to demonstrate and maintain technical superiority throughout these years has been underpinned by a continued dedication by those who have forgone the glory of winning todays fight to think strategically about the future wars and what research and development is required today to win those fights. Since 2001, the US's focus has justifiably shifted to the War on Terror, and the ever-present battles over the budget each year have worn away the DoD's funding for R&D. Likewise, the Nation's top leadership has focused on winning these battles, and maintaining the training and force structure necessary to do so successfully. But as our attention has been focused elsewhere, we have gradually allowed the realm of future R&D to languish with a lack of concentration.

The Department of Defense is a monolithic creature that has evolved over generations with intelligent, well-intentioned leadership. With each generation of emergent challenges, every organization strives to maintain relevancy in its environment and develop processes to best achieve the organization's mission. Without, and sometimes with deliberate intervention from a higher source, every organization has adapted for its own needs, and the morphology of the system has become more difficult to comprehend and to navigate.

Within the DoD, within the world of acquisition, and within the space domain, lies nestled a complex system which we will call "space R&D". Specifically, this thesis highlights the complexity of the space R&D enterprise – with many distinct entities conducting R&D, each navigating complex governance structures and competitive funding processes. Moreover, these entities act with little enterprise-level guidance regarding overarching domain-specific priorities. First, we focus on the organizations throughout the DoD that are currently conducting R&D for space technology, and how these various entities are steered, funded and governed.

We will then examine what principles and tools are best practices for technology maturation planning and portfolio management, with a special emphasis on using Model-Based Systems Engineering (MBSE). We then incorporate these best practices into recommendations for future governance of space R&D, with MBSE as a baseline functional tool. By defining future use cases using a solution-neutral functional architecture, we can identify specific tracks of technology development that must be achieved to meet that functional architecture. Some technology development will contribute to all mission areas, such as advances in propulsion, power, communication data rates, and computing. [5] Each mission area may rely on these advances to different degrees, however, thus it is critical to capture the dependencies between functional components. Other mission areas may rely more heavily on the development of specific technology components, such as specific sensor capabilities, in order to achieve significant evolution of the architecture.

As our space enterprise becomes more interdependent, it is essential that we consider new advancements in technology for application across all mission areas. If a new capability that has cross-functional applications is advanced, it needs to be quickly understood and evolved for incorporation across the space enterprise. We need to break out of our pipeline focuses, and consider early in the acquisition process how advances across all areas of core technology enablers might be applied to maximize each mission area.

The process for uniting all of the activities leading up to the start of a program of record, which we will call the Pre-Acquisition Process, will be outlined with clear ownership for each function. Additionally, systems engineering methods and tools will be proposed that will facilitate the communication, collaboration, coordination, cooperation, and centralization for the Pre-Acquisition Process. With the recognition that large, complex systems are slow to maneuver, we will also consider intermediate steps that can be taken to begin steering the Department efforts toward an objective state.

Ultimately, this thesis will describe a new approach to conducting the entire process for R&D in the DoD Space Enterprise, using new methods and tools to aid decision makers, and a more streamlined governance process for the entire system.

2.3 Scope of Work

There are two ways to bound the US space problem today. We use the term DoD Space Enterprise to bound all DoD entities and DoD-funded activities related to space systems. If we expand the boundary to include the other government agencies outside the DoD, then we use the term National Security Space (NSS). This thesis is focused on aligning the DoD Space Enterprise under a common governing body, so that we can centralize our knowledge and decision making for the best interests of the entire DoD. If we were to expand the boundary to NSS, we lose the authority to govern centrally.

Although part of the new Principal DoD Space Advisor (PDSA's) role is to better work with external entities such as the Intelligence Community to align all National Security Space efforts, the PDSA does not have authority to direct policy, priorities, or spending decisions for these external organizations. Therefore, this thesis will only address the DoD Space Enterprise, with the understanding that the NSS would be welcome to participate in all or parts of the processes outlined for better alignment.

Chapter 3 BACKGROUND

This chapter will first discuss the DoD acquisition process, to understand where the technology maturation feeds into major defense programs, and where the requirements pull for this technology originates. We will then examine how R&D is conducted across the DoD, including the DoD-level funding and oversight, then focus in on the space enterprise beginning with the oversight of space R&D. Next we will walk through each of the entities within the DoD conducting space R&D, including their own governance and funding structures. Finally, we will discuss the launch opportunities for space technology demonstrations. Throughout this chapter, we will attempt to clarify the multitude of personnel, committees, steering groups, working groups, and boards that set priorities and make decisions about the conduct of space R&D.

3.1 ACQUISITIONS

The Acquisition process for the Department of Defense is a remarkably complex system that spends billions of dollars each year to support the warfighter. [6], [7] Although having sufficient R&D available to begin the process is a critical component, the management of R&D is very segregated from the acquisition process.

The overall acquisition process for the DoD is governed by three decision-making systems, the Joint Capabilities Integration and Development System (JCIDS), the Planning, Programming, Budgeting and Execution (PPBE) Process, and the Defense Acquisition System (DAS). In short, these can be thought of as the three processes for requirements, funding, and execution, although all 3 systems play a part across the entire lifespan of a program. [8], [9] Each of these systems is overseen by a different part of the Department of Defense. The JCIDS process is managed by the Joint Staff, through the Joint Requirements Oversight Council (JROC) and chaired by the Vice Chairman of the Joint Chiefs of Staff (VCJCS). The PPBE process is managed by the Office of the Secretary of Defense (OSD), through the Deputy's Management Action Group (DMAG) and chaired by the Deputy Secretary of Defense (DEPSECDEF). And finally, the Defense Acquisition System is overseen by the Defense Acquisition Board (DAB), which advises the Under Secretary of Defense for Acquisition, Technology and Logistics (USD/AT&L). The Milestone Decision Authority (MDA) for each specific acquisition program is also a key decision maker in the DAS.

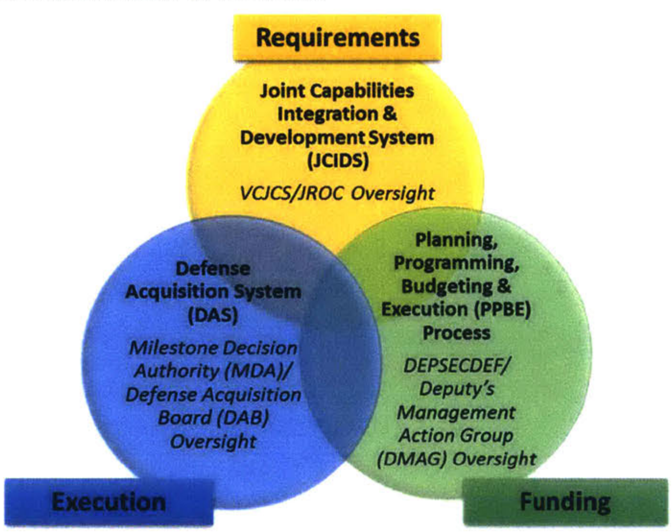


Figure 3-1. Traditional DoD Decision Support Systems (Source: Adapted from Defense Acquisition Guidebook) [10]

Figure 3-2 shows the typical progression through the acquisition process. Each of the requirements documents developed through the JCIDS process are illustrated, in conjunction with the acquisition phases governed by the DAS and its associated gate reviews, or Milestone Decisions. Both of these processes inform the PPBE process, which identifies and allocates funding to correspond with acquisition decisions.

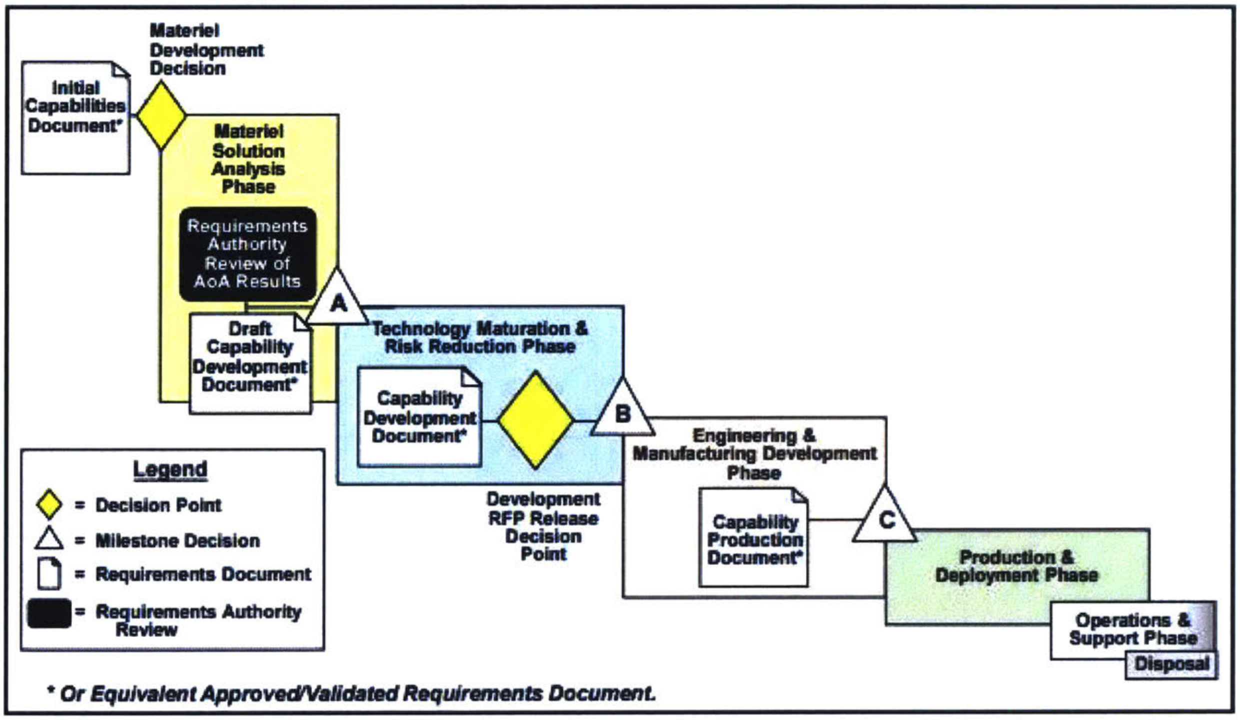


Figure 3-2. Illustration of the Interaction Between the Capability Requirements Process and the Acquisition Process (Source: DoDI 5000.02, January 7, 2015 [8]*)*

This process begins when a need is identified, and a Capabilities Based Assessment and Capability Gap Assessment (CGA) are conducted to flush out any validated requirements that do not have material or non-material solutions. An initial capabilities document (ICD) is then generated to document the capabilities and gaps that have been deemed unacceptable risks. Prior to the Material Development Decision, a plan must be developed for conducting an Analysis of Alternatives (AoA), which dominates the Material Solution Analysis (MSA) Phase. As described in DoD Instruction (DoDI) 5000.2,

> The purpose of this phase is to conduct the analysis and other activities needed to ***choose the concept for the product*** *(emphasis added)* that will be acquired, to begin translating validated capability gaps into system-specific requirements including the Key Performance Parameters (KPPs) and Key System Attributes (KSAs), and to conduct planning to support a decision on the acquisition strategy for the product. AoA solutions, key trades among cost, schedule, and performance, affordability analysis, risk analysis, and planning for risk mitigation are key activities in this phase. [8]

What these three systems do not govern, however, is the R&D leading up to the initial steps of the acquisition process. So where do these concepts come from? The MSA phase is essentially the beginning of a product development process, but in order for an AoA to be conducted successfully, there must be a sufficient "shelf" of technologies from which to choose. The available collection of technologies to address the capability gap must be broad enough to allow for varied approaches and concepts, and must be advanced enough that the technology has been sufficiently demonstrated to reduce the risk of new development during the acquisition process.

Milestone B is where a program is officially designated and funded as a program of record, and part of the Milestone B decision framework requires a Technology Readiness Assessment (TRA) that justifies that the level of risk is acceptable for any critical technologies, including any demonstration of the technology in a relevant environment. [11] The DoD has learned over many years that trying to integrate technology that has not been sufficiently developed will lead to costly overruns. [12]

The United States Government Accountability Office (GAO) has identified two of the biggest drivers in acquisition problems as being a lack of technology maturity and attempting to achieve too much in a single acquisition evolution. [13]–[15] The first problem is driven by programs that are initiated before the technology has advanced enough that the cost and schedule for implementation can be well understood. Rather than taking a mature technology and integrating it into an operational system, too many programs have done the development work as part of the acquisition system, and suffered cost and schedule delays when the technology proves harder to advance than expected. The second problem is that acquisition programs tend to try to address all of their future requirements in a single evolution of the constellation, rather than a gradual progression or upgrades. [15] Often, once a program appears to have support and a strong chance of being funded, the community rallies and tries to include as much new capability as potentially possible. This results in large, complex systems with a multitude of new technology advancements in development concurrently, which results in costly overruns when problems occur and resonate across the system.

Accordingly, it is critical that the DoD R&D process feeds the acquisition process by developing a collection of technologies that can be advanced to a sufficient level that their feasibility and technological purpose can be demonstrated and then "shelved" until such time that they are needed for development into a specific product. Figure 3-3 shows conceptually how prioritized technology projects should be shepherded and advanced until it is available for transition into an acquisition program.

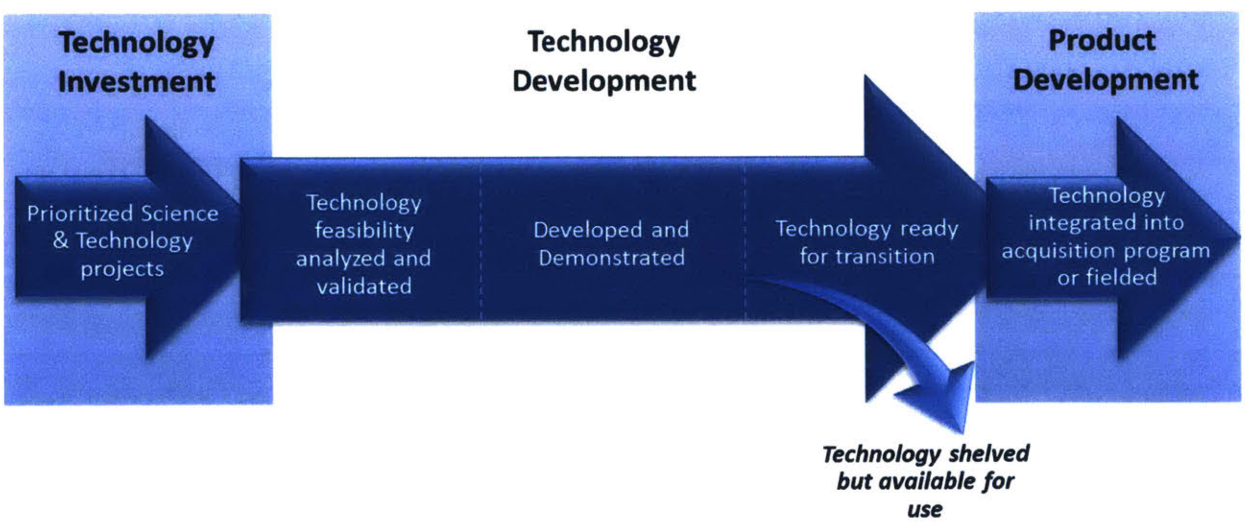


Figure 3-3. DoD Technology Management (Source: Adapted from GAO analysis of DOD S&T management process [16]*)*

When capability gaps dictate a new program of record be considered, an AoA is then conducted to analyze the best solution of all the available technologies for fielding in an operational system. In the past two years, the DoD has conducted AoAs for three of its most critical mission areas, including environmental monitoring (weather), missile warning, and protected communications. Challenges with each of these AoAs highlight that the DoD is struggling to adequately plan for future AoAs, and a lack of deliberate technology development and planning is resulting in lackluster AoA options. [13], [14]

In a review of the Space-Based Environment Monitoring (SBEM) AoA, the GAO found that although the process was sufficient in identifying the capability gaps, it failed to adequately coordinate and collaborate with critical stakeholders, and incorrect assumptions failed to consider the full spectrum of solutions. In these mission areas, the DoD now faces critical capability gaps without solutions, and must do additional analysis outside of the AoA process to develop solutions. [17], [18]

In addition to these AoAs, Congress directed another assessment of the Space-Based Infrared System (SBIRS) GEO 5/6 satellites to consider adding new technology, rather than building repetitions of the previous design. [3] A GAO review of the assessment concluded that it was too late to realistically consider options for the next generation of satellites, and that more technology insertion should have been planned into the acquisition strategy over time to aid the acquisition for the future generation system. [3], [14] Further, the report concluded that upgrades to future satellites are being planned solely based on technology obsolescence issues and isolated technology opportunities, rather than a clear development plan for the mission area. [3]

Because of the challenges with these acquisition programs and AoAs, the GAO has recommended that technology "discovery" needs to be separated from an acquisition program. [15] Meaning, we need to do a better job advancing technology to the point of adequate demonstration, so that it can be properly evaluated in an AoA and more smoothly transitioned to a program of record.

3.2 DoD R&D Governance

3.2.1 DoD-Level R&D Governance

The Assistant Secretary of Defense for Research and Engineering (ASD(R&E)) is the senior leader responsible for R&D across the DoD. The ASD(R&E) chairs the Science and Technology (S&T) Executive Committee (ExCom), which provides oversight, prioritization, and strategic guidance to the R&D enterprise. ASD(R&E) strives to manage R&D through a portfolio management approach, named *Reliance 21*. There are, however, an estimated 10,000 unique science and technology projects across the DoD, thus the enterprise was decomposed into 17 technical portfolios, called Communities of Interest (COIs) to integrate technical efforts within specific technical categories, such as space. [19], [20]

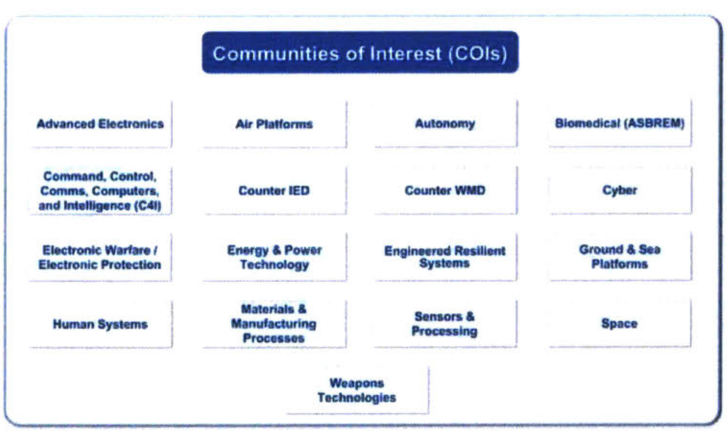


Figure 3-4. Decomposition of the ExCom into 17 Communities of Interest (Source: ASD(R&E) [21]*)*

The goal of the Space COI is to:

1) Facilitate collaboration and leveraging of complementary investments of the space S&T efforts performed by the DoD, Intelligence Community, the National Aeronautics and Space Administration (NASA), the Department of Energy (DoE), the National Oceanic and Atmospheric Administration (NOAA), the commercial space industry and, as appropriate, Allied and friendly nations in support of the intent of the nation's Space interests; and

2) Identify gaps, establish and maintain a set of S&T roadmaps to guide Space Community research program investments, perform portfolio assessments, and provide future resource recommendations to leadership. [22]

The COIs are intended to include senior leaders that can influence the technical policy and decision making within their own organizations, although the group in itself is only empowered to make recommendations to the ExCom for decisions. Figure 3-5 shows the roles and responsibilities of each level of participant in the COI, beginning with the small Steering Group which focuses on prioritizing the gaps and opportunities. The COI is then broken into technical sub-groups to focus on the specific mission areas. The lower two levels are merely representative of the community which this group is meant to represent.

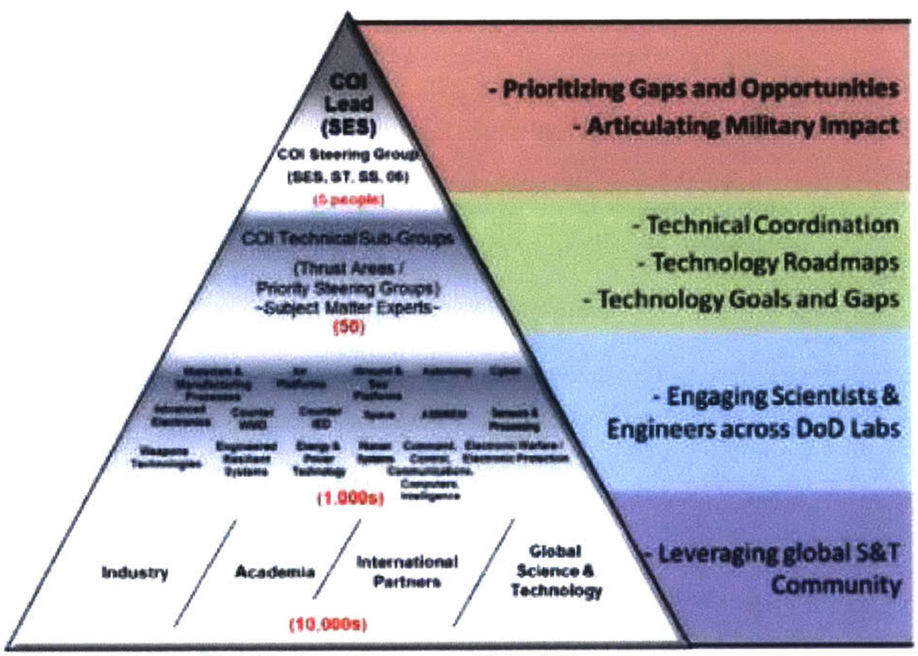


Figure 3-5. Communities of Interest Makeup and Roles [21]

It should be noted, that as a separate effort to better align R&D information for the DoD, the ASD(R&E) office has created the Defense Technical Information Center (DTIC) to serve as a repository for all DoD-funded research information, to facilitate exchange, reduce duplication, and provide a forum for streamlining information sharing. [20]

3.2.2 R&D Funding

The Department of Defense budget for fiscal year (FY) 2016 was more than $580 billion, with $188 billion going towards acquisition programs, including R&D. [6] The specific category of funding we are discussing in this thesis, is referred to by the DoD as "Science & Technology" funding, which encompasses Basic Research (6.1), Applied Research (6.2), and Advanced Technology Development (6.3). [23]

6.1 Basic Research	Basic research is defined as systematic study directed toward fuller knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind. Basic research, however, may include activities with broad applications in mind.
6.2 Applied Research	Applied research is defined as systematic study to gain knowledge or understanding necessary to determine the means by which a recognized and specific need may be met.
6.3 Advanced Technology Development	Development is defined as systematic application of knowledge or understanding, directed toward the production of useful materials, devices, and systems or methods, including design, development, and improvement of prototypes and new processes to meet specific requirements.

Table 3-1. DoD Science and Technology Funding Category Descriptions (OMB Circular A-11 [23]

This funding made up $13 billion, or approximately 2.25% of the total DoD budget for FY16. The breakdown between each of these funding levels can be seen in Table 3-2. [6]

Base budget $ in billions

Program	FY 2016 Request	FY 2016 Enacted*	FY 2017 Request	FY16 Enacted – FY17 Change
Basic Research (6.1)	2.1	2.3	2.1	-0.2
Applied Research (6.2)	4.7	5.0	4.8	-0.2
Adv Tech Dev (6.3)	5.5	5.7	5.6	-0.1
Total S&T	**12.3**	**13.0**	**12.5**	**0.5**

****Reflects Congressional adds to include $100 million for Technology Innovation efforts, $250 million for the Defense Rapid Innovation Fund, and $204 million in support of Army, Navy, Air Force, Defense Agencies, and university research programs.***

Table 3-2. DoD Science and Technology Program Funding (Source: FY 2017 Budget Request [6]*)*

While specific projects in the Advanced Technology Development may be identified as space enterprise related, it is difficult to break out the Basic Research (6.1) and Applied Research (6.2) funding as space-domain only. Many times, research in these categories may mature to influence technology in several different domains. We will examine this funding stream as it flows to each of the organizations conducting research in space-related technology areas, however, to understand the complicated oversight mechanisms and decision making entities that guide and influence the expenditures of this $13 billion each year.

3.3 DoD Space Governance

Space acquisitions are incredibly complicated because of the demanding physical environment, broad span of users and stakeholders, and complex interfaces across the DoD. [13] The number of stakeholders involved in a single space system acquisition can be staggering, and yet they must follow the same PPBE, JCIDS, and DAS processes as any other DoD system. To navigate these processes, the Air Force has been designated as the lead Service for the DoD Space Enterprise, and Air Force Space

Command (AFSPC) is the Air Force Major Command (MAJCOM) with responsibility for space superiority. [24], [25]

Navigating the DoD on behalf of space has proven challenging, and the Secretary of Defense has modified the governance structure several times to attempt to give the Air Force better authority to carry out this directive. The creation of the Defense Space Council (DSC) was meant to bring senior leaders across the National Security Space to review and discuss enterprise issues. While this group achieves a holistic look at the issues it chooses to examine, it is made up of a diverse group of stakeholders with their own interests at stake, and no single decision making entity has authority over the entire enterprise short of the DEPSECDEF. [15] The GAO has released several reports on this subject, and summarized:

> Past studies and reviews have found that responsibilities for acquiring space systems are diffused across various DOD organizations, even though many of the larger programs, such as the Global Positioning System and those to acquire imagery and environmental satellites, are integral to the execution of multiple agencies' missions. This fragmentation is problematic because the lack of coordination has led to delays in fielding systems, and also because no one person or organization is held accountable for balancing government wide needs against wants, resolving conflicts and ensuring coordination among the many organizations involved with space systems acquisitions, and ensuring that resources are directed where they are most needed. [15]

In October 2015, the Secretary of Defense (SECDEF) recognized that the "DoD requires a governance structure that monitors and oversees the performance of the entire DoD space portfolio and provides cogent and analytically- supported programmatic recommendations to departmental leadership." [26] Thus, SECDEF modified the previous oversight construct to help better coordinate these efforts, and created a new designation for the Secretary of the Air Force, as the Principal DoD Space Advisor. In this role, the PDSA is now the advisor to all three oversight groups within the acquisition process, in addition to acting as the primary advisor for all space matters for the Secretary of Defense, Chairman of the Joint Chiefs of Staff, and all Senior DoD officials. [26], [27]

Thus, the new DoD Decision Support System can now be represented as in Figure 3-6, which shows the new PDSA role influencing each of the acquisition processes.

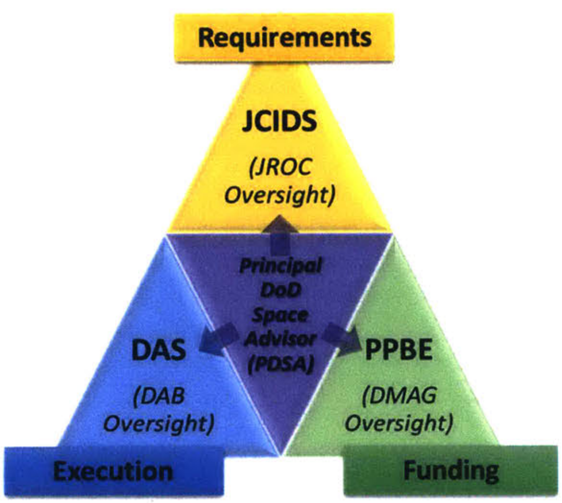


Figure 3-6. New Space Oversight of DoD Decision Support Systems

Although the Air Force acquires and operates the predominance of the space enterprise, each of the Services, as well as several other DoD and other government agencies, play a large role in the space architecture and operations. Thus, the PDSA, as the chair of the DSC, must coordinate this oversight amongst all stakeholders, including the Undersecretaries of Defense for Acquisition, Policy, Comptroller, and Intelligence; the Joint Staff; US Strategic Command; each of the Military Departments; Cost Assessment and Program Evaluation (CAPE); General Counsel; Chief Information Office (CIO); and National Reconnaissance Office (NRO), in addition to all other DoD elements with space programmatic authorities. Clearly, gaining consensus of this diverse council can prove challenging, thus the role of the PDSA has been strengthened to provide independent recommendations and assessments to the DEPSECDEF, in the event that the DSC does not reach agreement.

Although the PDSA authorities have been designated, and a staff has been established to fulfill this role, space R&D still falls under the ASD(R&E) office, and is not tightly integrated with the rest of space acquisition. For the ASD(R&E) office, space is just one of many technical areas that must be managed, and yet space R&D is happening in many different DoD organizations, through many different avenues. It is an incredibly complex problem to manage, making communication, collaboration, cooperation, and coordination very difficult.

3.4 Space R&D

3.4.1 Organizations Conducting R&D for the DoD Space Enterprise

Research & Development in the DoD is conducted at many levels, across many different entities. "These DoD activities perform one or more of the following functions: science and technology, engineering development, engineering support of deployed materiel and its modernization." [28] Figure 3-7 shows the many entities in this enterprise conducting R&D for space systems, both internal and external to the DoD. The external organization, such as NASA, International Partners, and the Intelligence Community are included due to the complex relationships and partnership programs that contribute to the advancement of technologies for the space domain. The challenge we face as the DoD, is that each there are still many different funding sources, governance structures, and processes for feeding technology into the acquisition process.

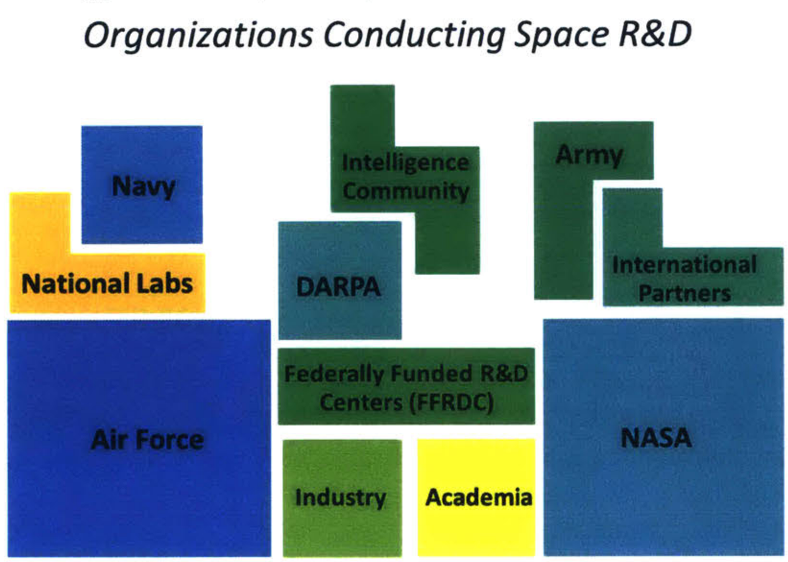


Figure 3-7. Organizations Conducting R&D for Space Systems

Each of these organizations is currently conducting R&D that will feed matured technology into the acquisition process with the intention that it will transition into a program of record. We will next examine how this R&D enterprise as a whole is managed at the DoD level, and then dive into the unique governance for each entity in the DoD Space Enterprise.

3.4.2 DoD Lead for Space- Air Force

The Air Force is leading the efforts to integrate the space portfolio, which includes all of the entities developing technology for space. In a recent review of Air Force development planning by the National Research Council, AFSPC and SMC were credited with having an "exemplar integrated space portfolio." [29] Indeed, the Space and Missile Systems Center (SMC) and AFSPC have made great strides to improve the oversight and integration of the space portfolio, bolstered by Gen John Hyten, Commander of Air Force Space Command, and the release of his Commander's Strategic Intent, list of Prioritized Space Superiority Activities, and most recently, his Space Enterprise Vision. These guidance documents give the Air Force a more clear direction about where we intend to go in the future, and this section describes how the existing processes work to take that future vision and execute R&D to meet the future capability needs.

The Deputy Assistant Secretary of the Air Force for Science, Technology, and Engineering (SAF/AQR) is responsible for developing AF policy and strategy, and program oversight of the entire AF S&T budget. The current process for Air Force developmental planning requires that a MAJCOM is designated the Core Functional Lead, responsible for developing a Core Function Support Plan (CFSP). [30], [31] The Air Force MAJCOM, AFSPC, is the lead command for space capabilities, and has been designated the Core Function Lead Integrator (CFLI) for Space Superiority, and is thus responsible for the organizing, training, and equipping for the space capabilities and systems. [24], [25], [32] AFSPC's acquisition arm for space system development and acquisition is SMC. [25] The research entity that feeds SMC is the Air Force Research Laboratory (AFRL), with the predominance of space research occurring in the Space Vehicles Directorate (RV) and the Aerospace Systems Directorate (RQ).

Figure 3-8 shows the DoD-level oversight as discussed in the previous section, and also shows the many levels and sources for strategic guidance that drive the R&D planning for space systems. This figure was developed from third party sources, primary source interviews with key stakeholders across the DoD, and 13 years of experience working in the DoD Space Enterprise.

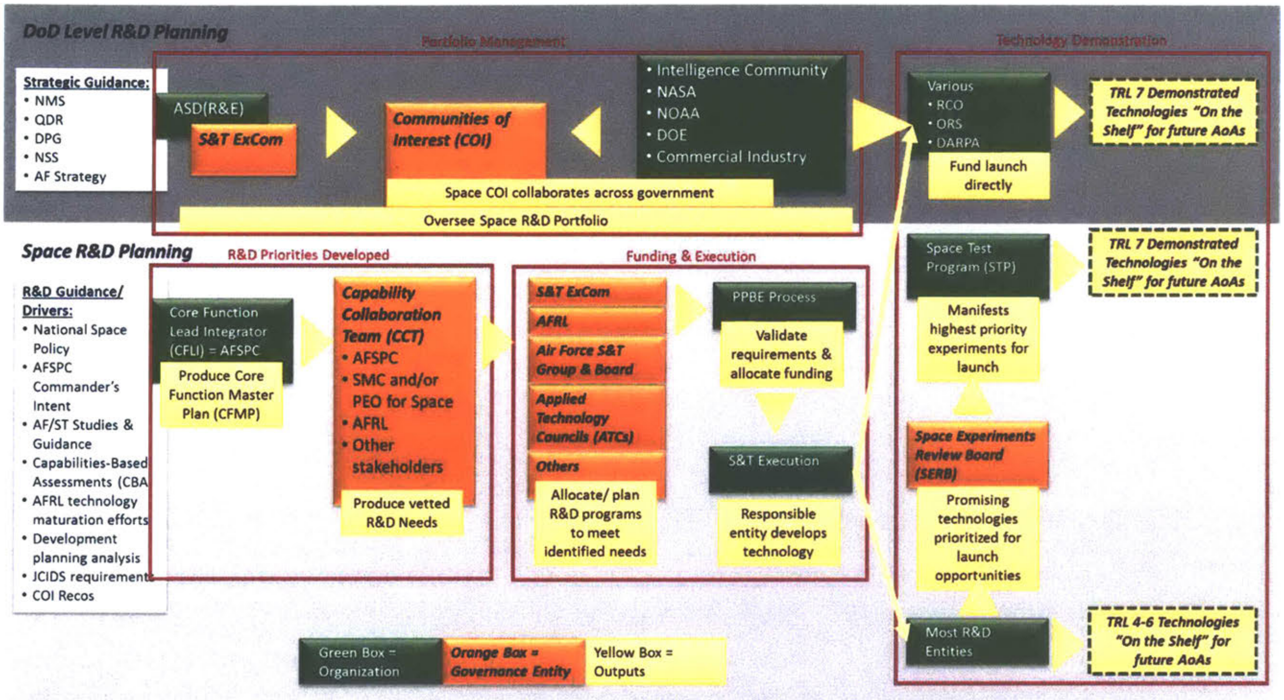


Figure 3-8. Simplified Space R&D Process (Source: Modified from [24], [25], [30], [32]*)*

At the highest level, the Space COI is charged with collaborating with other government agencies conducting space R&D, overseeing the S&T portfolio, and developing and maintaining a roadmap. [22], [33]

R&D priorities are analyzed and developed by AFSPC, as the CFLI, and documented in a CFMP. The Capability Collaboration Team (CCT), also led by AFSPC, produces a vetted list of R&D needs, and then makes recommendations to one of the guidance entities that manage the many different processes for executing R&D for space systems. [24], [25], [30], [32]

Figure 3-9 shows an additional level of detail for the "Governance and Execution" box from the previous figure, highlighting that the establishment of an R&D project can happen through several different avenues. Some projects are established directly with Air Force organizations such as the AFRL, the Rapid Capabilities Office (RCO), and the Operationally Responsive Space (ORS) office. Others have to go through a variety of governance boards to be funded.

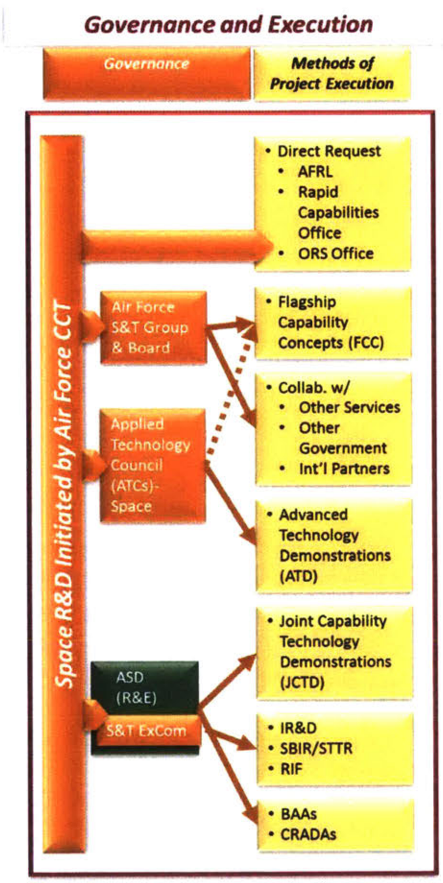


Figure 3-9. Detailed Space R&D Project Governance and Funding (Source: Modified from [32]*)*

The Air Force S&T Group and Board govern projects identified for Flagship Capability Concepts (FCCs), and also execute any projects that are directed towards other Services, other government agencies, or international partners for execution. The Applied Technology Councils (ATCs) govern all Advanced Technology Demonstrations (ATDs), and also conduct an annual review of the entire investment portfolio to ensure the investments are meeting the capability needs identified in the CFMP. [30], [32] OSD governs any technologies that are identified for consideration for a Joint Capability Technology Demonstration (JCTD).

Although the CCT may recommend a specific need be addressed by one of the governance entities specified, each must then work with a specific research organization to plan and execute the project. The funding for each of the methods of execution varies, but each of these organizations takes their planned project for solving the R&D need through the PPBE process for funding, and then executes through their own governance processes, as described in the next section.

The end result of this myriad of processes is that technology is matured, and demonstrated as some Technology Readiness Level (TRL). Most R&D entities funded through the process will complete the technology maturation to a TRL of 4-6. In order to demonstrate technology to a TRL 7, a prototype must be demonstrated in an operating environment. For space technology, this means it must be demonstrated on-orbit. Most projects matured to a sufficient level that they are capable of a space demonstration, will go through the Space Experiments Review Board (SERB) for a launch opportunity. [34], [35] Some projects and some specific offices will fund directly for the launch opportunity themselves. All external DoD space partners, such as the NRO and NASA, fund for their own launch opportunities as well.

A detailed description of the many R&D entities conducting space research is given in the next section, including the type of space research they conduct, how they are governed, and how they are funded.

3.5 RESEARCH ENTITIES CONDUCTING SPACE R&D

Within the DoD Space Enterprise, there are many different organizations and methods being used to fund innovation. The most prevalent entities conducting R&D for space include:

- Service Corporate Research Laboratories
  - Air Force Research Laboratory (AFRL)
  - Naval Research Laboratory (NRL)
  - Army Research Laboratory (ARL)
- Federally Funded R&D Centers (FFRDC)
  - The Aerospace Corporation
  - Massachusetts Institute of Technology: Lincoln Laboratory (MIT LL)
  - Sandia National Laboratories
- Defense Advanced Research Projects Agency (DARPA)
- Academia
- Industry
  - Independent Research and Development (IR&D)
  - Cooperative R&D Agreements (CRADAs)
  - Support Small Business Innovation Research (SBIR)
  - Small Business Technology Transfer (STTR)
  - Rapid Innovation Fund (RIF)

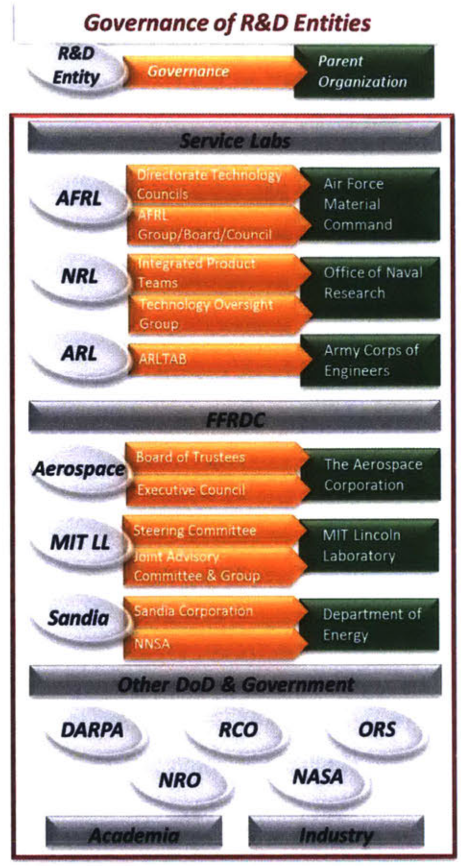


Figure 3-10. R&D Entities Governance (Source: Consolidated from Section 3.5)

Each of these organizations supports the DoD Space Enterprise in critical ways, but each is governed and funded differently. Figure 3-10 summarizes each of the R&D entities, how they are governed, and their parent organization.

The following sections will examine the way each of these R&D entities is governed at the DoD and, when applicable, the Service levels. It will also summarize the magnitude of funding that each organization is executing, and how decisions are made about the portfolio of investments.

3.5.1 Service Corporate Research Laboratories

The Defense Research Laboratory Enterprise consists of over 62 unique labs and geographical locations, and 35,000 scientists and engineers. At the DoD level, the strategic guidance comes from the ASD(R&E) through the ExCom, while the Research Directorate is responsible for the entire enterprise. [19] The primary missions of the Research Directorate are to oversee the work and workforce in the labs, and conduct technology readiness assessments for USD(AT&L) to inform the acquisition process. [36]

At the Service level, each of the Services has a unique governance and funding process for prioritizing its R&D. A summary is given here, to demonstrate how space technologies are being addressed through a variety of means.

3.5.1.1 *Air Force Research Laboratory (AFRL)*

The Air Force Research Laboratory organizationally falls under Air Force Material Command (AFMC), but works directly with AFSPC for the space domain requirements. AFRL is divided into nine technology directorates, with nearly 10,000 employees around the world. [37] Space technology research primarily occurs in the RV and RQ directorates, although many of the directorates have contributing efforts, including the 711th Human Performance Wing, and the Sensors Directorate. RV executed about $200 million in 2015, and focuses its work in four technical mission areas, including space situational awareness, space communication and position, navigation and timing, intel, surveillance and reconnaissance; and defensive space control. RV also has a small satellite program to provide support for small satellite demonstration of space technologies. [38], [39] RQ spends about $510 million annually on propulsion, power, and air vehicles for aircraft, space, and missile applications. [40]

Funding for the AFRL comes from two sources. In 2014, AFRL executed approximately $4.4 billion for the 6.1, 6.2, and 6.3 categories (see Table 3-1) of S&T directly funded by the Air Force. AFRL also receives funding from other Services and government agencies for specific projects. [37] Fiscal guidance is provided by the AF with any specific priorities, but the funding is divided by AFRL between the nine directorates. Each year, the Commander of AFRL releases a Commander's Intent, which acts as the Corporate Investment Strategy and fiscal guidance for the organization's budget development for the Fiscal Year Development Plan (FYDP). The guidance used to develop this strategy includes the "AF Strategic Master Plan, Core Function Support Plans, and inputs from Office of the Secretary of Defense (OSD), the Secretary of the Air Force (SECAF), the Major Commands (MAJCOMs), Scientific Advisory Board (SAB) results, and current year S&T program execution." [41]

The director of each directorate then manages his or her budget, and prioritizes the investments against two guiding elements. Each directorate also has a Directorate Technology Council (DTC) that assists the director with the investment decisions and portfolio management. [42] First, the director must align the investments to the warfighter requirements, as communicated in the applicable CFSPs for that directorate. For space, the CFSP has been developed by AFSPC, and specific capability needs have been identified and communicated through the AFSPC CCTs. The director must then map all of these planned investments against the core technical competencies that have been developed for the lab, of which there are 40 total. In this investment approach, each director must try to balance the immediate needs of the warfighter with the more broad set of technical skills that the AF believes are critical. [43] The DTC assists with this portfolio management, and conducts assessments and reviews of each program to ensure they are meeting the identified missions, and to ensure external programs are aligned with the directorate's strategic vision and are an appropriate use of AFRL's resources. [42]

Throughout the PPBE process, there are several reviews of the planned investments, at the corporate AFRL, Air Force, and OSD levels. Additionally, as described in Section 3.4.2, the entire investment portfolio is reviewed annually by the Applied Technology Councils, to ensure the planned investments align with the CFSPs. [41]

3.5.1.2 *Naval Research Laboratory (NRL)*

The Navy conducts critical research for the DoD Space Enterprise in areas that impact the operational environment for the Navy. The Office of Naval Research (ONR) is the organization within the Navy that oversees and executes research to support future naval warfare needs. ONR manages the 6.1, 6.2, and 6.3 portions of the Navy's RDT&E budget, which totals about $2 billion per year, or 1% of the total Department of Navy budget. [44]

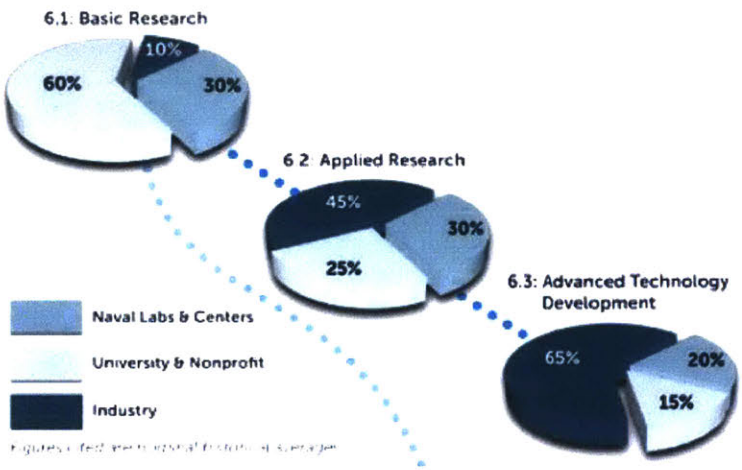


Figure 3-11. Historical Breakdown of the ONR S&T Budget (Source: Naval S&T Strategy,[44] *)*

The ONR is organized in several different, cross-cutting ways. Figure 3-12 shows the six Departments which managed the nine focus areas for all S&T research. Each of these focus areas is led by an Senior Executive Service leader, who is responsible for maturing and progressing technologies from early research through transition into acquisition programs. Along the left side of Figure 3-12, are the two Directorates within the ONR. The Office of Research manages the earlier stages of R&D, including the basic and applied research, and manages both the research conducted at the NRL and through the University Research Initiative (URI) (discussed below). [44]

The Office of Technology focuses on maturing specific technologies that are being "pulled" from the fleet and acquisition communities, through the Future Naval Capabilities (FNC) program. Through this program, technologies are matured to a TRL 6, at which point they will be transitioned to the acquisition process for additional funding and maturation. [44], [45] Primarily, technologies for space systems will be transferred to the Space and Naval Warfare Systems Centers (SSCs), which are the Navy's acquisition arm for information dominance, including those provided by space capabilities, under the management of the Space and Naval Warfare Systems Command. [46]

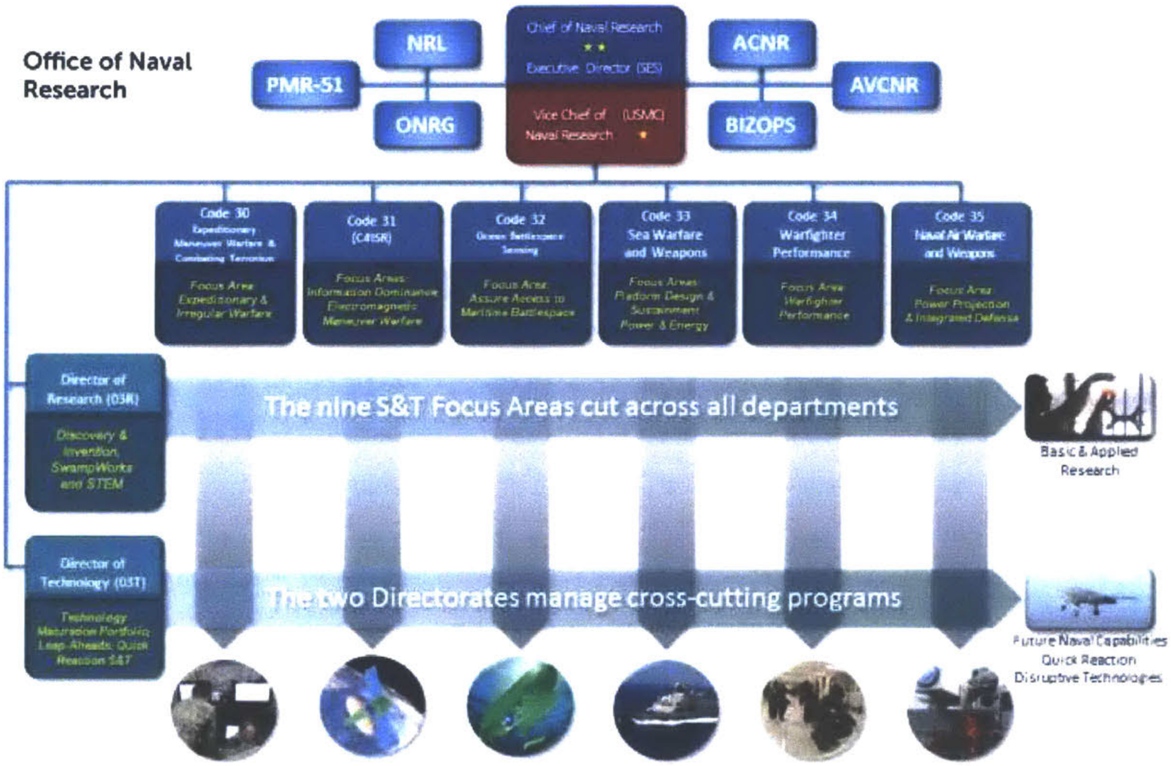


Figure 3-12. Organizational Structure of the Office of Naval Research (Source: Naval S&T Strategy [44]

For transition of specific technologies, the FNC program overseas nine pillars, or functional areas for technology development. Each of these pillars is managed by a two-star level Integrated Product Team (IPT), who conduct capability gap analyses that are then approved by the Technology Oversight Group (TOG). The IPTs then propose and prioritize a list of specific enabling capabilities (ECs) that will be matured over a three to five year period to meet those gaps, which are approved by the TOG and budgeted and executed by the ONR. In order to track the effectiveness of this process, each project is reviewed in its final year of S&T funding by the Technology Review Board (TRB), for an assessment of whether the technology has been or will be successfully implemented or deployed. The success rate for the FNC process is currently between 55 and 68 percent, although approximately 50 percent of the projects that "failed" to be transitioned were still deemed valuable by the TRB, and could be leveraged for future programs if new requirements emerged. [45]

The funding of all S&T is managed by the ONR through annual Investment Balance Reviews (IBRs). The Chief of Naval Research considers the funding guidance he or she has received from the Navy, and issues internal funding guidance to each program (including the NRL), generally trying to balance ~45% for basic research & applied science, ~30% for technology maturation, ~12% for leap-ahead innovations, and ~8% for quick reaction S&T. [44], [45]

Unlike the other Services, the Naval Research Lab is not funded directly by appropriated funding, but is funded through the Naval Working Capital Fund, where all costs are covered by sponsor-funded research projects. Figure 3-13 shows the approximate sources of funding over the last 5 years, with about 61% of funding coming from the Department of Navy, and 39% coming from the other Services, DoD, and other government sources. [46] Most space related R&D occurs in the Naval Center for Space Technology, which is one of four technical Directorates in the NRL.

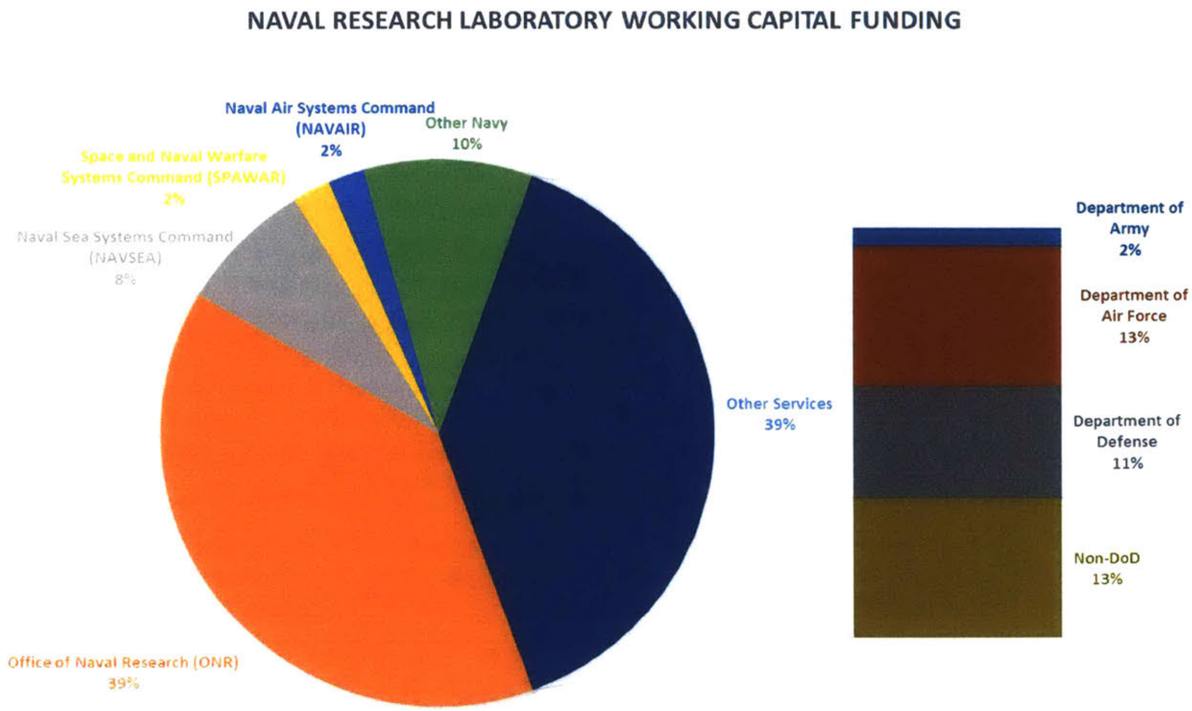


Figure 3-13. NRL Working Capital Funds Summary (Source: FY2017 Budget Justification, Naval WCF [46]

The NRL has organized its research into seven focus areas, including Space Research and Space Technology. The research conducted in this area supports the Navy's operational use of the space domain, including "command, control, communications, computers, intelligence, surveillance and reconnaissance, precision navigation and timing, orbital tracking, space situational awareness, maritime domain awareness, and the fundamental understanding of geophysical phenomena and natural radiation sources as pertain to space-based and complementary terrestrial systems." [47]

3.5.1.3 Army Research Laboratory (ARL)

Army R&D is managed by the Army Corps of Engineers, Research & Development Directorate. The corporate research laboratory is the Army Research Laboratory (ARL), which serves both the Army Material Command (AMC) and Army Research, Development, and Engineering Command (RDECOM). [48], [49] The ARL is organized in six technology directorates, and an Army Research Office.

In 2013, ARL developed an S&T campaign strategy that synchronizes research activities across eight campaign areas, guiding the capabilities for the future through 2040. Also in 2013, the ARL Director created an Army Research Laboratory Technical Assessment Board (ARLTAB) through the National Academies of Sciences, Engineering, and Medicine to conduct a biennial assessment of the ARL. The ARLTAB is assisted by up to seven panels, aligned with the new campaign areas. [50]

This research campaign strategy can be seen in Figure 3-14. This shows the process from idea generation, through prioritization and selection, into the final incorporation into programs within each campaign.

Figure 3-14. ARL Research Campaign Strategy (Source: ARL [51]

In ARL's 2015-2035 S&T Campaign Plans, there are several areas of collaboration with the Air Force for space systems, including chemical science research for the "development of materials for active holographic display for real-time battle surveillance from space," as well as information science research that contributes to space situational awareness sensors and data fusion. [52] The predominance of Army research that contributes to the DoD Space Enterprise is related to ground-based used equipment that integrates or utilizes space-based assets. This is an important aspect of a space system, but is often difficult to align with the other segments of the system due to stovepiped decision making between the Services.

3.5.2 Federally Funded R&D Centers (FFRDC)

In 1947, the US Air Force created the first FFRDC, called RAND. As of June 2015, the government was sponsoring a total of 43 independent FFRDCs, 11 of which are sponsored by the DoD, and one by NASA. At least 8 of these FFRDCs conduct some research related to the space enterprise. [53], [54]

FFRDCs are private-sector entities that are funded through a special relationship with the government to conduct long-term research and development. FFRDCs must operate independently and objectively for the government, and the DoD requires that they must be owned by a non-profit organization or linked to a college or university. Most importantly, they are designed to conduct R&D for the government, but are not allowed to compete with a non-FFRDC for any development to keep them free of any organizational conflicts of interest. [55]

The staffing levels of FFRDCs are generally constrained by Congress, to avoid any growth that might emerge as an avoidance of other established R&D processes. Generally, FFRDCs operated under a 5-year agreement with their sponsor, outlining their specific role. FFRDCs are often valued for their unique capabilities, flexibility, and support as an unbiased extension of the government, providing technical expertise in specific areas. [53], [56]

We will examine three representative examples of FFRDC that contribute to R&D in the DoD Space Enterprise here, although each FFRDC is funded and directed through different means within the US government.

3.5.2.1 The Aerospace Corporation

The Aerospace Corporation was established in 1960, and today primarily supports the Air Force space enterprise, both at SMC and at the NRO, supporting the DoD and NSS enterprise. Aerospace also supports several other government agencies with its 3,600 employees. The breadth and history of Aerospace's support to the DoD Space Enterprise is vast, but includes launch certification, system-of-systems engineering, systems development and acquisition, process implementation, and technology application. In 2015, Aerospace executed $916 million in contracts. [57] In 2014, Aerospace spent $835 million in federal financing, of which 2% was for basic research, 6% for applied research, and 92% development. [54]

Aerospace conducts its R&D through the Physical Science Laboratories, which is a collection of more than 80 specialized labs supporting advanced space systems. These labs conduct R&D for future technology development, as well as to support ongoing programs through independent research and testing. [58] The organizational structure of Aerospace allows the personnel supporting the space acquisition and development efforts to reach-back to the research laboratories for specific subject matter expertise, independent testing, analysis, and assessment.

Aerospace is guided by a Board of Trustees, which oversees corporate policy and the management of the company, and elects the Executive Council. The Executive Council are the senior management of the company, responsible for overseeing the vision, values, strategy, and performance. [57]

3.5.2.2 MIT Lincoln Laboratory

MIT LL was first established in 1949 as an FFRDC to develop the first air defense system for the United States. Today, it conducts R&D for all military Services, OSD, the intelligence community, and other government agencies. MIT LL employees over 4,200 staff to achieve the lab's two primary technical objectives, "(1) the development of components and systems for experiments, engineering measurements, and tests under field operating conditions and (2) the dissemination of information to the government, academia, and industry." [59] MIT LL is divided into eight technical divisions, which cross ten mission areas. Space system development would generally fall under Division 9, Space Systems and Technology, but could cross divisions in multi-disciplinary projects. [60] MIT LL also maintains several collaboration arrangements, such as the MIT LL Beaver Works Center, a joint collaboration between MIT LL and the MIT School of Engineering to provide "an incubator for research and innovation." [59]

MIT LL funding comes from a variety of appropriated sources, and is administered by ASD(R&E). Figure 3-15 shows the breakout of funding by mission areas, with the red highlighted area on the far right showing the basic and applied research. [61] In 2014, MIT LL received $827 million in federal funding, less than 1% of which was basic research, 90% was applied research, and 9.5% for development. [54]

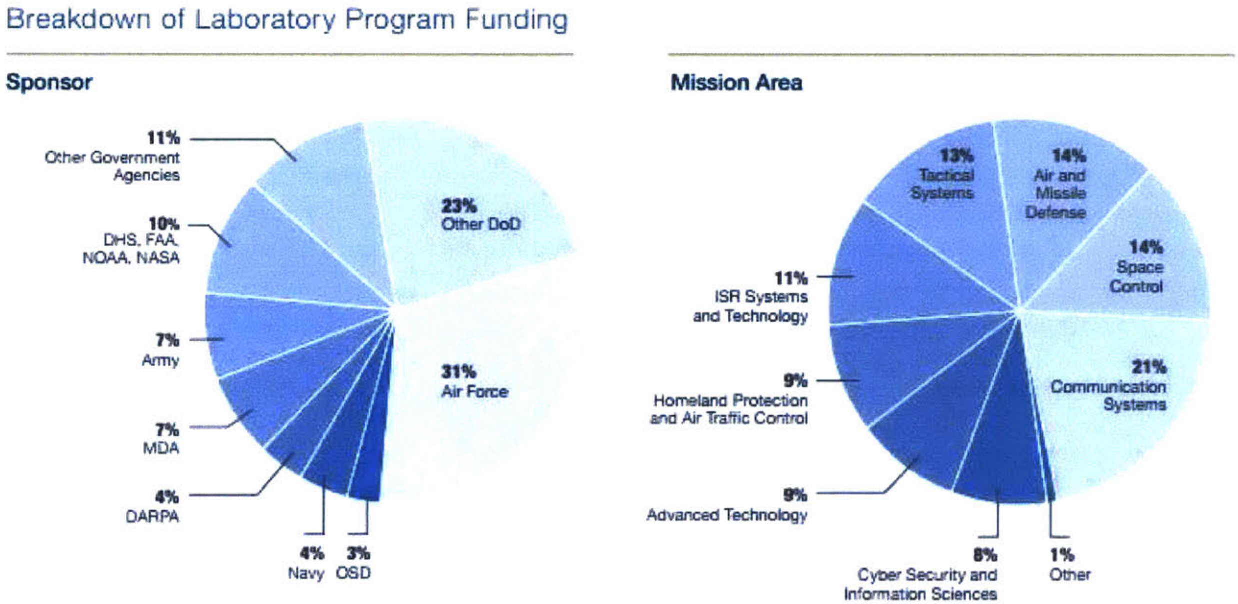


Figure 3-15. MIT LL Funding Breakdowns (Source: MIT LL Fact Book 2015, [59]*)*

MIT LL is governed by an internal Steering Committee, which is led by the Director's office and the heads of each technical division. Government oversight is conducted through a Joint Advisory Committee (JAC) and JAC Executive Group. The JAC is made up of primary stakeholders from key sponsoring agencies, including the Principal Deputy ASD(R&E), Assistant Secretary of the Air Force for Acquisition, Director of the NRO, Commander of AFRL, Assistant Secretary of the Army (AT&L), Assistant Secretary of the Navy for Research, Development, and Acquisition, and Deputy Director of DARPA. This group reviews the LL planned programs annually, as well as the five-year plan for the FYDP. [60]

3.5.2.3 Sandia National Laboratories

Sandia National Laboratories is operated by the Sandia Corporation, which is a wholly owned subsidiary of Lockheed Martin, but is isolated from Lockheed Martin in a unique Government Owned Contractor Operated arrangement. Sandia's total funding was about $2 billion in FY 2014, primarily funded through the DoE. It also executes significant research efforts through Strategic Partnership Projects, for the Department of Homeland Security (DHS), and other federal agencies, including about $730 million for the DoD. [62] These funds are managed directly by the Services that have formed agreements with Sandia to conduct research on their behalf.

Since the 1960's, Sandia has designed sensors and ground processing systems to detect nuclear detonations. Sandia is also known as a world leader in the surveillance technology known as synthetic aperature radar, "a type of radar able to produce high resolution, photo-like images of terrain and structures day or night and in good or bad weather." [63] Due to Sandia's primary focus on reducing the threat of nuclear proliferation, several other space applications have emerged from the lab's research, including radiation hardening of components for space, materials testing, engineering solutions and microelectromechanical systems (MEMS) designs for space, and nuclear power for space systems.

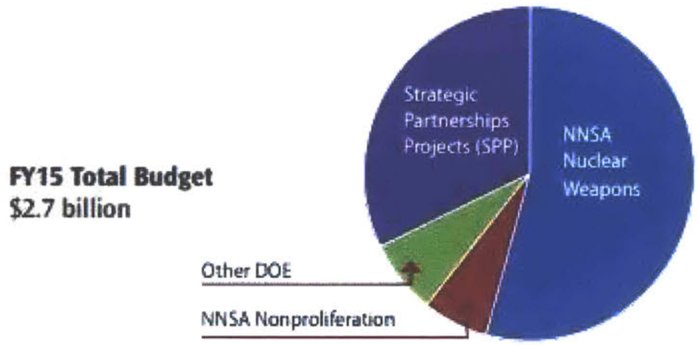


Figure 3-16. Sandia National Lab Funding (Source: Sandia Strategic Plan) [62]

3.5.3 Defense Advanced Research Projects Agency

Since its inception in 1958, DARPA has been at the forefront of innovative research for the United States. Credited with developing the first weather satellite in 1959, co-developing the Corona program with the National Reconnaissance Office in 1960, and launching what would become the precursor to the GPS constellation, also in 1960, DARPA has led the world of space systems development through its unique culture and portfolio approach- only tackling truly difficult problems. [64] DARPA is known for its driving culture, where projects are only permitted if they meet the "DARPA Hard" test. Project managers are constantly challenges to only take on high risk, high reward type projects that are so innovative that no one else has considered, tried, or achieved them. [65]

The governance of DARPA is very flat. There are only 220 government employees, in 6 offices. Approximately 100 of these employees are program managers, who report directly to the 6 office directors. All programs are approved and reviewed by the DARPA Director and Deputy Director, who also set priorities and balance the investment portfolio. [64]

Despite its historical successes in space systems, DARPA remains on the outskirts of the DoD Space Enterprise, not fully engaged in the bureaucracy of the R&D or acquisition processes. DARPA succeeds in putting technology on the shelf for future consideration, but there are no clear maturation plans that feed DARPA's word into explicit programs of record. Each project is handled case-by-case, and whether the technology will transfer into an Air Force space acquisition program if often dependent on timing and opportunity.

In 2016, DARPA received a total of $2.9 billion for research and development. Of this, $127 million was dedicated for space programs and technology. This included several programs such as Airborne Launch Assist Space Access (ALASA) ($29 million) and Experimental Spaceplane One (XS-1)($30 million), both looking at reducing the cost of space launch; and Project Phoenix ($19 million) and Robotic Servicing of Geostationary Satellites (RSGS) ($10 million) aimed at developing suitable methods for servicing satellites already on-orbit. Each of these projects has anticipated partnerships with the Air Force, Navy, or commercial sector, but none have been specifically identified for follow-on funding or implementation by the Services. [66]

3.5.4 Academia

The federal government is the largest source of funding for R&D work in universities, according to a survey by the National Science Foundation, which received data from 895 degree-granting institutions spending at least $150,000 in R&D each year. Figure 3-17 shows that Federal government funding (not including funding from the American Recovery and Reinvestment Act of 2009) made up approximately 57% of R&D funding for universities from 2010 to 2014. [54]

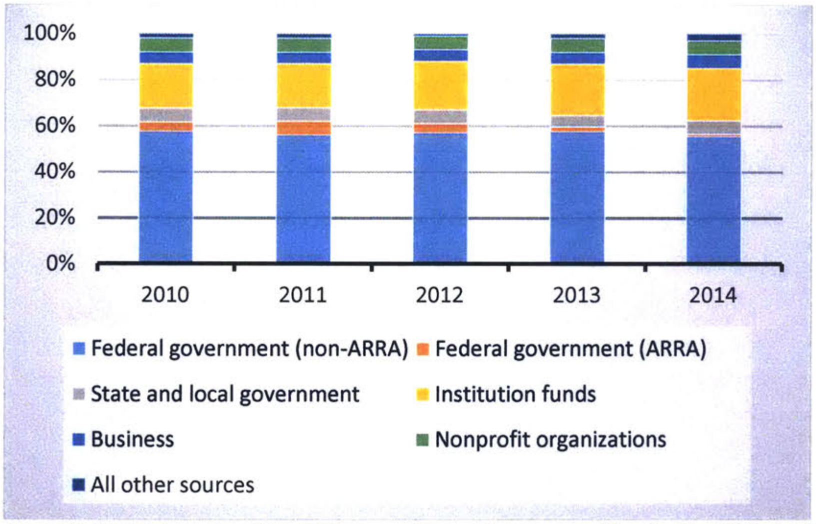


Figure 3-17. Higher education R&D expenditures, by source of funds: FYs 2010–14 (Source: Chart modified from National Science Foundation data [54]*)*

In 2014, the DoD spent more than $2.7 billion for R&D in universities, $2.1 billion of which was for basic research and advanced technology development. [54]

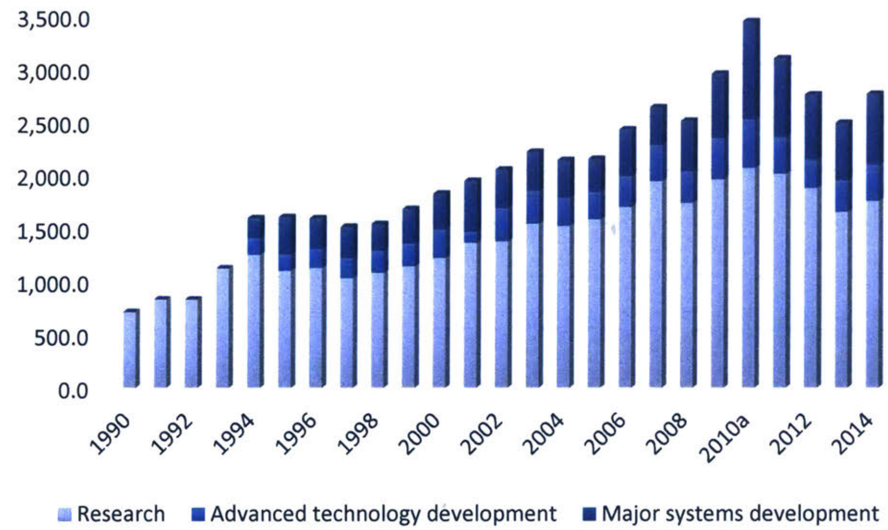


Figure 3-18. Department of Defense obligations for science and engineering research and development to universities and colleges, by type of activity: FYs 1990–2014 (Source: Chart Modified from National Science Foundation Data [54]*)*

The programs used to fund academic research vary widely across the DoD. Much of this funding is actually transferred via FFRDCs, through partnerships and other collaborative programs as described at MIT LL. Some is transferred directly from the Services to the universities. The Army, Navy, and Air Force each budget RDT&E funds under basic research for the University Research Initiative (URI). In 2016, the Services budgeted a total of $361 million for this program, broken out in Table 3-3 by Service. [6], [46], [67]–[69]

Account Title	Organization	FY 2016 Total Enacted
Research, Development, Test & Eval, Army	ARMY	72,603
Research, Development, Test & Eval, Navy	NAVY	146,196
Research, Development, Test & Eval, AF	AF	141,754

Table 3-3. University Research Initiative (Source: DoD FY 2017 Budget Submission [69]*)*

These programs are overseen by the Department of Defense (DoD) Science and Technology (S&T) Executive Committee, but managed and executed by the AFRL, ARL, and NRL. Funds are spent through fellowships, competitive grants, and independent research awards, focused on expanding basic knowledge of relevant science and technology areas. [67], [70] As this funding is for basic research, it is not broken out into specific applications for the technology, such as space.

Each of the Services manages this program differently, but in the Office of Naval Research, more that 80% of ONR-sponsored S&T is executed through academia, industry, and the research community. To evaluate the success of this research, annual peer reviews are conducted for each project to ascertain the merit, risk, originality, and accomplishment. These results are used to make adjustments in funding, and for consideration in future transition. [45], [47]

Universities also receive direct funding from many of the lab and FFRDCs discussed previously. For example, AFRL and the American Institute of Aeronautics and Astronautics (AIAA) co-sponsor the University Nanosat Program (UNP) to partially fund student design, development, build, and potentially, launch opportunities for new space technology.

3.5.5 Industry

Industry has traditionally been one of the government's biggest partners in developing new technologies for space systems. Each year, many companies choose to allocate some internal funding for Independent Research and Development (IR&D or IRAD). Companies can also conduct research in response to Broad Agency Announcements (BAAs), and through CRADAs. Small businesses are also encouraged to participate in DoD innovation, with set aside funding through the SBIR, STTR, and RIF programs. The methods are plentiful, but the motivation and alignment with government needs are more difficult.

3.5.5.1 Independent Research and Development

SMC estimates, "there is over $2.0B IRAD dollars available for investment in approximately 12 NSS related companies whose total workforce numbers over 100,000." [71] The benefit to the companies conducting the research, is that they are permitted to claim a portion of their own investment as "overhead" on cost-plus contracts. This work, however, is not conducted as part of a contract, and thus the government oversight is limited. [72]

Oversight of IR&D has fluctuated wildly over the years, from tight regulation and heavy supervision until the early 1990's, to almost no oversight. The DoD is gradually trying to modify this governance, and today, ASD(R&E), as chair of the R&E EXCOM, has corporate DoD responsibility over IRAD projects. [1], [73] In 2012, the requirements for contractors changed, and they are now required to submit information about their IRAD projects to the government through the DTIC website if they plan to conduct more than $11 million in IR&D. [74] The use of this "Marketplace" has grown, and can now be used by all government entities, who can post strategic guidance that they feel will be helpful to industry. As of May 2016, the Strategic Documents site contained more than 90 links and documents for applicable R&D strategies, plans, concepts, visions, overviews, vectors, strategic plans, master plans, roadmaps, white papers, briefings, press releases, testimonies, presentations, and other assorted documents. [22]

In reality, what the DoD's industry partners are searching for is the best opportunity for them to apply their in-house investment and expertise to gain competitive advantage in the next business opportunity. [1] In addition to strategic use of IR&D, the largest of the defense development contractors will spend hours heavily blanketing their contacts in the DoD to try to understand the timing and priorities of the decision-makers, and to spread the word of their latest innovation efforts to capture attention. The smaller developers must be more selective, and focus their efforts on technologies that will influence procurement decisions in the very near term (1-3 years). [75]

Although the government generally appreciates industry's contributions to the R&D effort, there are efforts underway to improve the alignment and effectiveness of this spending. As part of USD(AT&L) Secretary Kendall's Better Buying Power 3.0 effort, he is considering changes to the rules regarding IR&D funding for defense contractors to reduce the use of IR&D for the express use to decrease the price of a competitive bid in future acquisitions. [76] For space technology, the Chief Scientist at SMC is working "to optimizing and maximizing the IRAD efforts is to coordinate existing efforts and programs (e.g., Small Business Innovation Research/Small Business Technology Transfer, Multidisciplinary University Research Initiative, Rapid Innovation Fund Program, DoD Technology Transfer Program, and Unified Research and Engineering Database)." [71] There is, however, still significant room for improvement in finding ways to better align the industry IRAD spending with the government technology priorities.

3.5.5.2 Broad Agency Announcements

In addition to IR&D, industry can pursue innovation funding through several DoD-sponsored programs. BAAs are a competitive process used by the government to request proposals for basic and applied research to advance scientific and technical knowledge for specific agency objectives, but not related to the development of a specific system or hardware procurement. [55]

3.5.5.3 Cooperative R&D Agreements

Any of the above mentioned government-funded R&D entities can choose to partner with industry using a CRADA or STTR arrangement. These arrangements are designed to provide a mechanism for a mutually-beneficial exchange of knowledge and technology transfer that will lead to technology investment that might not otherwise be feasible. [55]

3.5.5.4 Small Business Innovation Research and Small Business Technology Transfer

Two programs are managed for the entire US government by the Small Business Administration, called SBIR and STTR. These programs are designed to help small business, with less than 500 employees, conduct R&D in a way that will lead to technological innovation, meet federal needs, increase the industrial base, and opportunities for small businesses to profit from the commercialization of their work. [77]–[79]

The SBIR program is mandated to be 2.9% of the R&D budget for any agency conducting R&D of more than $100 million annually, which is then managed by that agency. Both the DoD and NASA participate in this program, which requires that they designate specific R&D topics for solicitation of proposals, then competitively award the funding. [77], [79] The STTR program is designed to partner small business with nonprofit research labs, universities, organizations, or FFRDCs, with the intent of fostering technology transfer to the commercial sector through the cooperative development and research of the technology. All agencies conducting $1 billion in R&D are required to set aside 0.3% of their extramural R&D budget for this program, which is administered by that agency. Again, both the DoD and NASA participate in the STTR program. [77], [79]

As seen in Figure 3-19, the federal government spent approximately $2.5 billion in 2015 through the SBIR and STTR programs. The DoD was the largest participant, awarding $1.07 billion in 2015. [77]

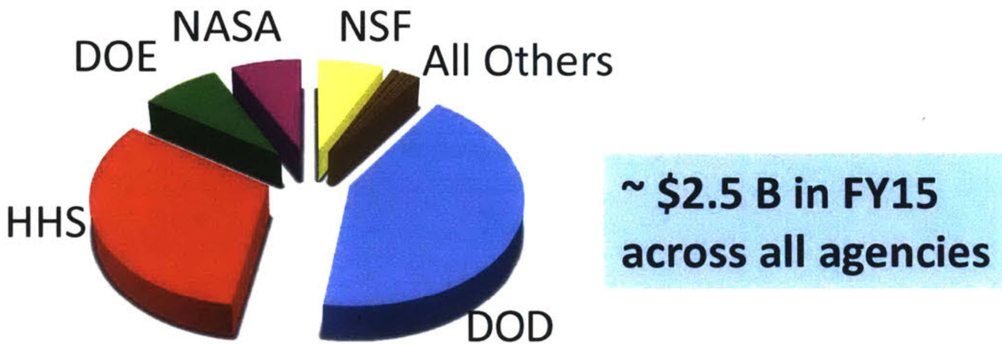


Figure 3-19. Estimated SBIR/STTR Budgets by Agency, FY2015 (Source: SBIR-STTR Presentation [77]*)*

With this funding, the DoD, led by the Office of Small Business Programs, under USD(AT&L), executes three rounds of solicitations for both SBIR and STTR each year, which results in about 15,000 proposals. This results in about 3,000 awards each year. [80], [78] Each Service, or organization within the DoD has a designated program manager for the SBIR/STTR programs. In the Air Force, this responsibility has been delegated to AFRL, who is responsible for collecting topics from across the Air Force acquisition and R&D communities and executing the programs. Approximately 40% of the topics for the AF come from the AFRL technical directorates, and 60% come from various Air Force centers. [78]

3.5.5.5 Rapid Innovation Fund

The RIF is another funding vehicle, targeting but not limited to small businesses, which is also managed by the Office of Small Business Programs. The DoD was appropriated $225 million in 2015, and $250 million in 2016, with a focus on achieving technology that can quickly be matured for transition into an acquisition program within two years, for less than $3 million. [81]

For the RIF, a BAA is first issued for specific topics of interest, which have been collected from all the same sources as the SBIR and STTR programs. White papers are then reviewed, and promising projects are asked to submit a proposal. Proposals are selected with the objective of maturing technology to a TRL of 6 or greater by the completion of the project. [81]

In 2015 the GAO released a report, reviewing the effectiveness of the RIF. It concluded that since the program began in 2011, 452 projects have been funded, from more than 11,000 white papers that were submitted. To assess the program, the GAO looked specifically at 52 projects that were funded in 2011, and scheduled to be completed by 2014. Figure 3-20 shows that 22 of these programs were transitioned successfully into acquisition programs or other users. [16] This is, by no means, conclusive about the success of the RIF program, but did suggest that the program has merit, and is successfully inserting some new technologies into the defense acquisition programs.

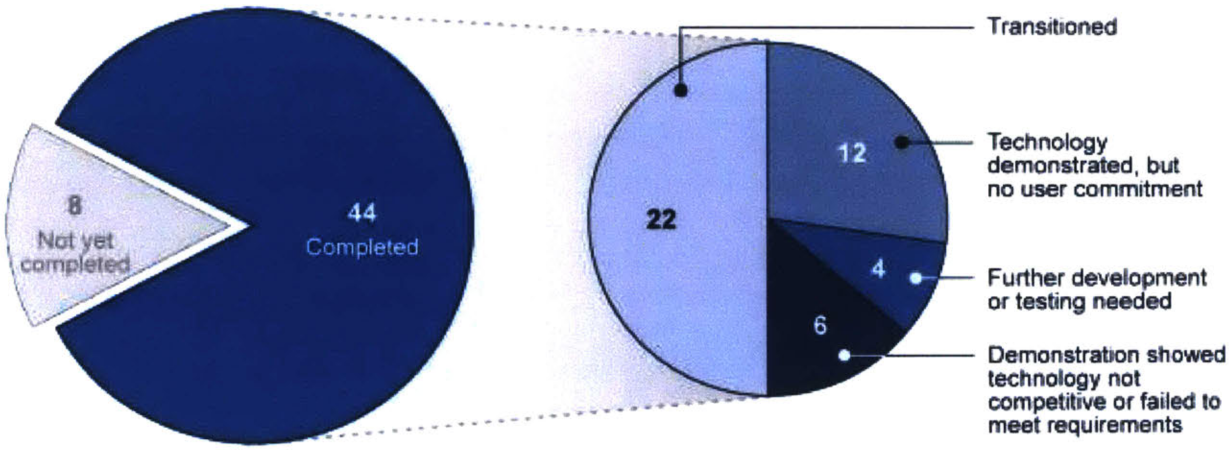


Figure 3-20. Transition of 52 Projects Scheduled for Completion by July 2014 (Source: GAO analysis of DoD data, GAO-15-421 [16])

3.6 Launch Opportunities for Space R&D

The final, critical stage in maturing technology for space-based systems is to demonstrate this capability in its operational environment. This has traditionally been the "valley of death" for space R&D funding, because it is still incredibly costly to put mass into space. [71], [82] R&D organizations don't have sufficient funding to launch prototypes or demonstrations for all of their promising technology, and program offices are hesitant to spend their limited funding on technology that has not yet been proven. Additionally, the launch opportunities are limited in orbital location, with most demonstration payloads being launched as secondary payloads from other primary missions, or from the International Space Station. Thus, the Air Force has developed a process for assessing all interested projects for launch, and assisting in obtaining a launch opportunity to demonstrate their technology on-orbit.

When a DoD entity has a new technology that they would like to fly as an experiment or demonstration, whether it is as a single instrument piggybacking on another spacecraft, a single spacecraft, or a series of experimental spacecraft, the technology is presented to an annual Space Experiments Review Board (SERB). The SERB is made up of voting members from the OSD, U.S. Strategic Command (USSTRATCOM), Army, Navy, Air Force, DARPA, MDA, the National Reconnaissance Office, and NASA. Each of these Services and government agencies prioritizes their experiments within, then forwards the prioritized list to the DoD-level SERB, where a single prioritized list for the year is developed. This list is then passed to the Space Test Program (STP) office, for evaluation and manifesting on the best available launch opportunities. [35], [83], [84]

The STP, is executed through SMC, in the Advanced Systems and Development Directorate (SMC/AD), and manages all SERB-prioritized missions, evaluating the best rideshare opportunities, which could be as an auxiliary payload (APL) on a DoD mission, through a dedicated STP mission, or as APLs on NASA or non-DoD missions. [83], [85] The STP subsidizes the launch costs for as many of these experiments as their budget will allow, but does not contribute to the funding for the development of the technology itself. Other programs bypass the SERB process entirely by budgeting for their own launch costs, and come to the STP for assistance with launch manifesting and integration only.

Currently, any experiments desiring a launch opportunity through the SERB submit a form describing their project. The SERB members each score the experiments, using a weighted consideration of military relevance (50%), experiment quality (40%), and service/agency priority (10%). The prioritization is not currently aligned clearly with other existing S&T governance bodies at the DoD or Air Force levels. [43], [84]

3.7 Assessment of Space R&D

While the Air Force has a functional process for guiding space R&D, there are still challenges at both the Air Force and DoD Space Enterprise levels. After 15 personal interviews with top officials in the DoD, it became clear that there is still dissatisfaction with the existing processes, duplication, lack of alignment, and state of R&D today. [43], [75], [84], [86]–[91]

3.7.1 Organizational Governance Structure

The first challenge, is that, in reality there are still many organizations tasking many different R&D entities. Despite all of the good intentions, the system has evolved to create several different organizations conducting capability gap analysis at various levels, using various tools and methods. We then try to wrap all of the analysis into a single list of priorities at the AFSPC level, but those priorities aren't well communicated or deliberately delegated to specific R&D entities to address in a cohesive way. As the funding processes vary for every organization, there may be multiple entities competing for the same funding to address the same capability gaps, without clear coordination at the enterprise level. And finally, only a subset of these promising technologies are advanced to the prototype or demonstration stage, without a clear maturation and transition plan.

Ultimately, the biggest obstacle in the governance for space R&D is that there is not a single responsible entity with ownership over the R&D efforts for the DoD Space Enterprise. Although SAF/AQR looks at the entire Air Force S&T program, this office doesn't have oversight over the other services, and isn't able to coordinate the space efforts across all the stakeholders. At the DoD level, ASD(R&E) oversees the entire DoD S&T program, but this is not aligned with the acquisition community managed by OSD(AT&L). A better governance structure would more clearly align the space-specific R&D efforts with the future acquisition needs across all aspects of the DoD.

3.7.2 Lack of Development Planning

The second challenge we face in the space R&D enterprise today, is that we face a lack of mature technologies, on the shelf, ready for assessment and consideration for our next generation AoAs. As discussed in Section 3.1, we are struggling to complete adequate AoAs that result in a clear program strategy. This is due partially to the decreases in R&D funding over the previous decades, but more likely is due to the lack of deliberate technology maturation and insertion planning to prepare for today. [3]

MITRE's Systems Engineering Guide suggests that strong technology planning must have a clear goal or end-state, with planned insertion points for the technology. [92] Although this is occurring in some limited scope within mission areas, it's not occurring in a comprehensive way across the space enterprise. Our current senior DoD leadership has demonstrated the last few years that they are interested in rectifying this lack of advanced thinking, from Mr. Kendall's BBP initiatives, to Gen Hyten's focus on developing clear priorities. [1], [4], [93], [94] But that doesn't change the fact that we are playing catch-up in some areas of R&D, and need to continue to strive to improve the existing processes to take the most advantage of the 35,000 researchers and engineers that want to solve our technology problems for the future.

3.7.3 Stovepipe Missions Areas

The third major challenge that inhibits progress in the space domain is the stovepiped nature of the existing systems and mission areas. The GAO has repeatedly cautioned the DoD that, "fragmented responsibilities in DOD space programs have made it difficult to implement new processes and coordinate and deliver interdependent systems." [14]

Acquisition decisions are generally made within a program segment, and sometimes across a mission area. Cross-program dependencies are not often considered, and acquisitions decisions made for the good of the program segment, not integrated across programs. [95] Integration of space, ground, user, and launch segments on multiple programs have faced overruns and misalignments due to the lack of a single oversight body to make decisions across the DoD. [14], [15], [95], [96] Additionally, stand-alone satellite control networks keep operations segregated and inefficient. [96]–[98]

The overall number of stakeholders involved in the acquisition of these systems with unique interests, and the fragmented nature of the oversight, present a huge challenge to the acquisition process. Add to that the lack of integration with the future R&D planning, and the lack of alignment is compounded. Without a systems engineering approach to the management of our R&D, we are potentially missing critical vulnerabilities caused by unforeseen interdependencies. At the same time, we may be neglecting tremendous opportunities through force multipliers and synergies that we haven't anticipated, and don't have a current method for exploiting.

While many of these oversight processes and R&D conducting entities are trying to realign themselves to look at cross-cutting capabilities, the existing space systems that generate requirements "pull" are still very isolated in their acquisitions and operations. When addressing his new Space Enterprise Vision, Gen Hyten highlighted,

> In the recent past, the United States enjoyed unchallenged freedom of action in the space domain. Most U.S. military space systems were not designed with threats in mind, and were built for long-term functionality and efficiency, with systems operating for decades in some cases. ***Without the need to factor in threats, longevity and cost were the critical factors to design and these factors were applied in a mission stovepipe*** *(emphasis added).* This is no longer an adequate methodology to equip space forces. [93]

The new role of the PDSA has been defined to try to address some of these concerns, but the PDSA staff has a challenging job to try to execute a methodical way of managing this complex enterprise. Aristotle is quoted as originating the phrase, "The whole is greater than the sum of its parts." [99] Today we are looking at our space capabilities as individual systems, and adding them to get the sum of technologies we can deliver to the warfighter. The remainder of this thesis will examine how we could approach the space domain as a whole, and find synergies between the space systems. By using Model-Based Systems Engineering and other systems engineering tools, we can examine the DoD Space Enterprise as a complex system, and properly analyze and govern the process in a more efficient and aligned manner.

Chapter 4 Modeling and Portfolio Management Best Practices

The International Council on Systems Engineering (INCOSE) defines systems engineering as,

> ... an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. [100]

Systems engineering is a critical component of our DoD acquisition programs. Our space enterprise systems are amazingly complex individually, and even more complex when considered as a single system within the DoD Space Enterprise system. Figure 4-1 captures the increasing layers of complexity that are being wrapped around every component we build today, resulting an increasingly difficult system to manage.

Growing Levels of Systems Complexity

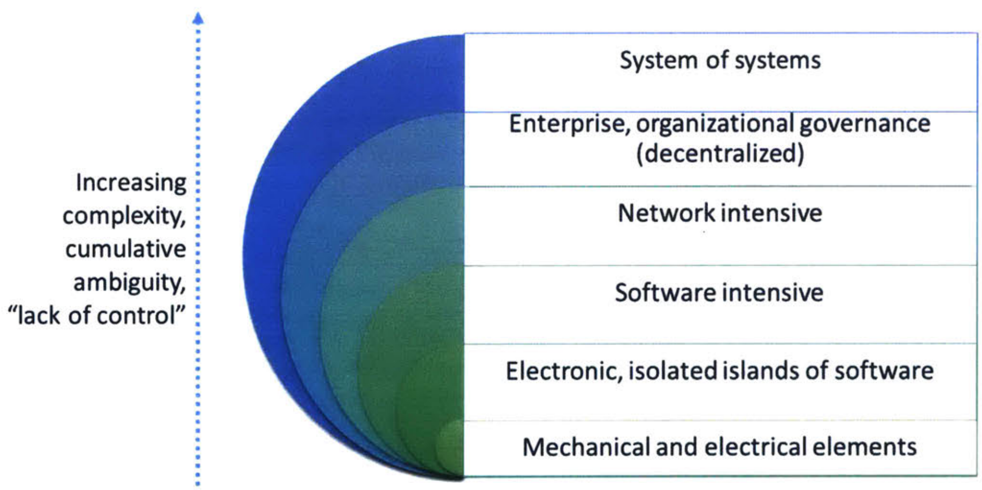


Figure 4-1. Growing System Complexity (Source: Adapted from INCOSE SE Vision 2025 [101]*)*

Although we have developed incredible capabilities within many mission areas, we have not yet managed to find a cohesive way of analyzing the systems across mission area boundaries. At the 2016 National Space Symposium, both Gen Hyten and Secretary Work spoke about the need to better integrate our systems of the future, to maintain technical superiority. [56], [102] Secretary Work specifically discussed the new 3rd Offset Strategy, which he explained requires "new combinations of technologies, operational concepts, and organizational constructs to maintain our ability to project overwhelming combat power into any theater and at times of our own choosing." [56]

To better do this in the operational environment, the Air Force has teamed with all of the stakeholders in the NSS to create the Joint Interagency Combined Space Operations Center (JICSPoC). The JICSPoC is focusing on how to improve our battle management and command and control in space, so that we can "fight through" a conflict in the space domain. [56], [102] As systems engineers and acquisition professionals, we must be thinking 10-20 years in the future with this new mindset, and developing a plan for how to better integrate and understand our space enterprise of the future. We must also take the lessons we're learning from the experiments in the JICSPoC, and use them to develop the system architecture of the future, to improve the integration and resiliency of the enterprise. Through many interviews conducted for this thesis, our senior leaders agreed that despite the many challenges we are faced, we can and must do a better job integrating our efforts in the DoD Space Enterprise. [43], [75], [84], [86]–[91], [103], [104]

This chapter is going to look at three different concepts that span systems architecture, systems engineering, and program management, that could jointly be used to help the DoD improve our R&D processes and better align the management for the future space enterprise. First, we will discuss the history of Model-Based Systems Engineering, and consider several case studies that have successfully implemented its use in space or DoD programs. Then, we will look at best practices in portfolio management and consider various methods that are used or could be better used in the DoD. We will also examine the use of a Design Structure Matrix as a tool to analyze the relationships between elements in a complex system. Finally, we'll consider the challenges and benefits associated with using these methods and tools, and some of the lessons learned that were shared during the many interviews with experts in these area throughout the preparation of this thesis. [86], [91], [103]

Chapter 5 will then lay out a step-by-step recommendation for streamlining the entire R&D governance process using each of these tools to facilitate and inform a better decision making process for the DoD Space Enterprise.

4.1 Model-Based Systems Engineering

One method growing in popularity in the systems engineering community is MBSE [105]–[109], which INCOSE defines as,

> Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE is part of a long-term trend toward model-centric approaches adopted by other engineering disciplines, including mechanical, electrical and software. [110]

MBSE is intended to improve systems engineering practices by evolving requirements, structural, behavioral, and simulation-based models in a single shared model, rather than their historic separate, domain-specific repositories. Figure 4-2 shows the evolution of a team from standalone, stovepiped models and system information shared through documentation to a centralized shared model. From this shared model, each team or use might have access to or views of data unique to their discipline, but built on a common baseline and most up-to-date system data.

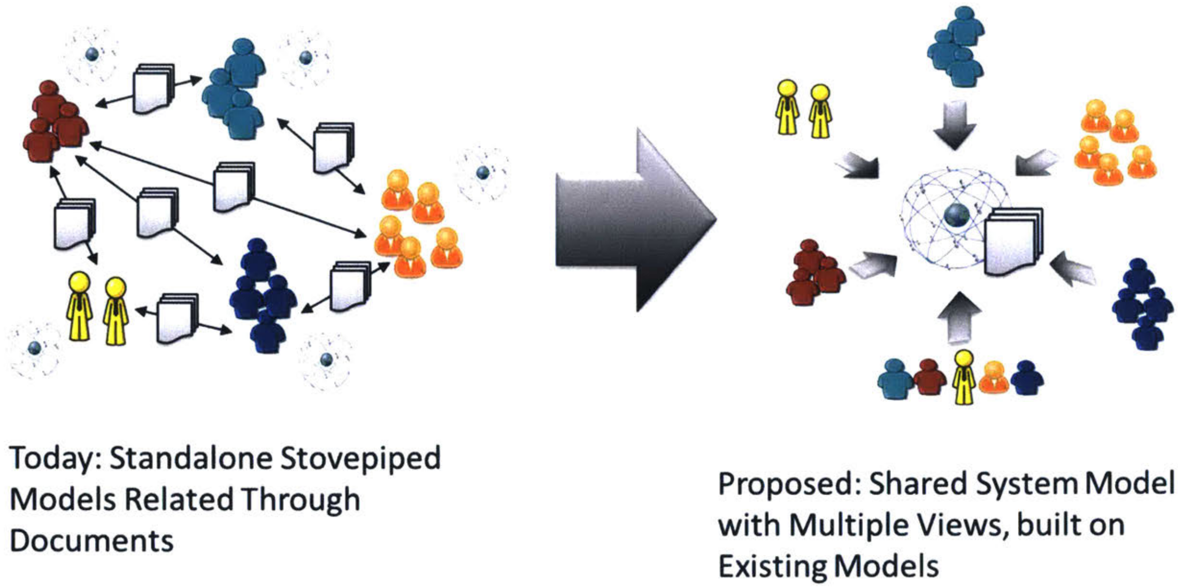


Figure 4-2. MBSE Shared System Model (Source: Adapted from JPL [111]*)*

One important element of this approach is the shift from document-based work to model-based work. MBSE proponents have emphasized the value in continuity, consistency, and accuracy of the data when it can be captured in a single location, with necessary documentation for gateway reviews auto generated from the model. This approach bypasses the need to update changes and data in multiple locations, and streamlines the information management and change management processes. [112]–[114]

MBSE is growing in popularity as a method for harnessing the power of systems engineering in a way that can capture both the complexity of an entity, the relationships between multiple entities, and the important characteristics necessary for analysis for a given purpose. One benefit of using models is that a complex system can be simplified and explained through abstraction, to both capture reality and eliminate unnecessary detail. Through the use of object-oriented methodology, abstraction can be applied by defining objects with the necessary level of detailed information, including use cases or concepts of operation (CONOPs). [112]

By combining the use of models with the systems engineering discipline, we can more effectively explore current and future system architecture decision space, communicate our future needs to a broader audience, and evaluate proposed solutions against not just one mission area, but against the entire spectrum of capability needs.

An MBSE initiative aimed at expanding the use of and growing the capabilities of MBSE is sponsored jointly by INCOSE and the Object Management Group (OMG), which has developed a set of international standards for the use of various graphical modeling languages. To claim use of MBSE does not require the use of any specific modeling language, which we will refer to as methods for MBSE. Additionally, some vendors have developed modeling language software packages to support MBSE, which we will refer to as tools.

4.1.1 Architecture and MBSE Methodologies

4.1.1.1 DoD Architecture Framework

The DoD Architecture Framework (DoDAF) is the DoD guidance for development system architectures, viewpoints, and models to support the JCIDS, PPBE, and DAS processes. In the recommended 6-step architecture development process, as seen in Figure 4-3, an architecture can be developed to communicate specific information to various stakeholders, ultimately to support decision maker needs. [115]

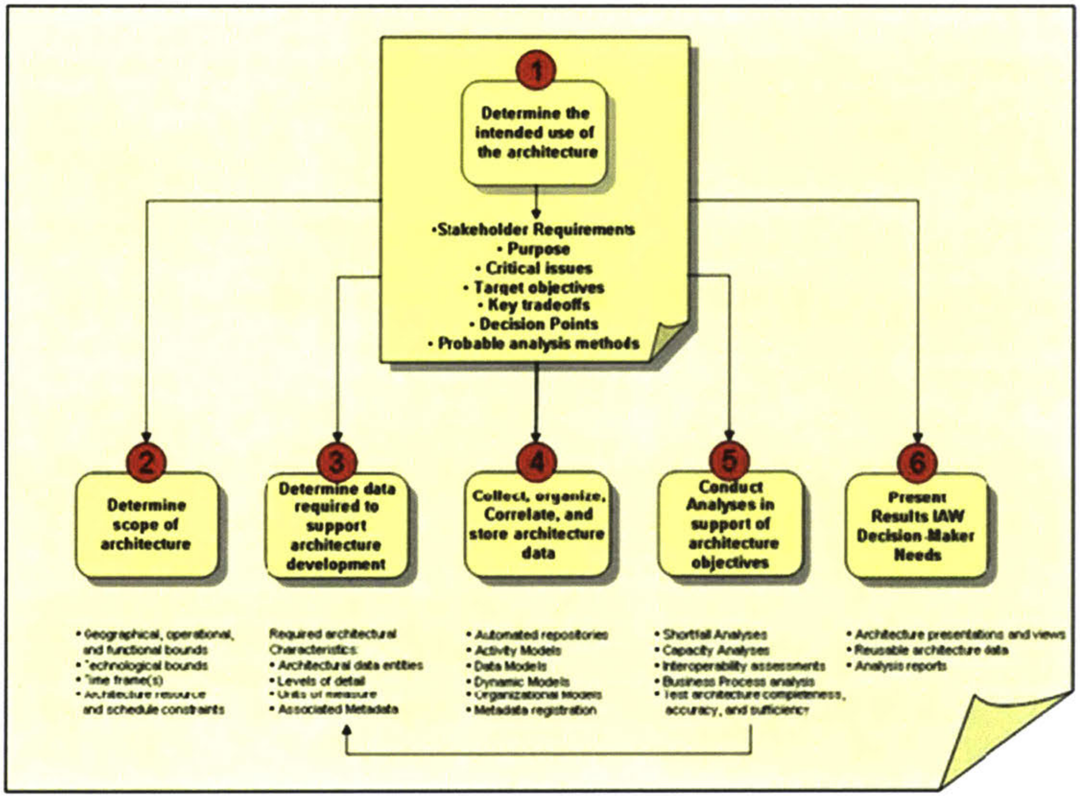


Figure 4-3. DoDAF Architecture Development Process (Source: DoDAF [115])

The DoDAF guidance outlines conformance requirements for a variety of core processes, including Capability, Data and Information, Operational, Project, Services, Standards, and Systems. [115] The DoDAF guidance is agnostic as to the tool used to create these diagrams, but focuses on ensuring a common ontology and content are shared for consistency across the Department.

Many of the viewpoints and models described in the DoDAF are pictorial representations of one aspect of the system, used to communicate a specific characteristic of the system in conjunction with a textual description. Other viewpoints may describe resource connections and flows, using lines and arrows, and boxes to represent an object. The benefit of using DoDAF viewpoints and models is that decision makers generally know what to expect when they are looking at a common viewpoint, and can usually interpret what each is meant to portray. The shortfall of the DoDAF is a diagram "key" is still required for every single viewpoint, because there is no single standard that defines what a box, line, or arrow is meant to portray. Within a program, each diagram may be built by a different engineer, and may be intended to convey a different meaning than the other, related diagrams. Additionally, these diagrams are often created as pictures or images in Power Point or other graphical software, and so any data meant to be shared must be pulled from its configuration-managed source, and must be communicated using text on the diagram. When changes are made to the system, not only must they be updated in their source document, but the DoDAF products must then be updated as well.

A more recent update to the DoDAF is the release of the criteria for the DoDAF Meta-Model (DM2), which defines the relationships between each of the viewpoints and models in the DoDAF. This additional guidance is meant to enable the consistent use of MBSE, so that the various models can be better aligned in a shared repository style model that captures not only the viewpoints, but the underlying data parameters as well. DM2 is meant to be method and tool-agnostic, so that users of the framework have the flexibility to develop the models using their preferred modeling languages, and using various vendor-developed tools, but in a way that will be consistent with other DoD programs. [116]

4.1.1.2 Unified Modeling Language (UML)

Dickerson's "A Brief History..." offers a comprehensive review of the history and evolution of basic modeling into the various MBSE methodologies that are common today. [117] Generally, these methods are rooted in the concept that a system can be modeled using objects, attributes of the objects, and relationships between the objects and their attributes. An object may represent a resource, component, or piece of the system, and can be decomposed into lower levels for additional details.

One of the graphical languages that has become prominent is the Unified Modeling Language (UML), a structured method used for modeling the architecture of software systems based on an object-oriented concept. The UML specification developed by OMG defines a total of thirteen different types of diagrams, in three broad categories, including structural diagrams, behavioral diagrams, and interaction diagrams. [118] These diagram types will be described in more detail below, but much as the DoDAF framework is meant to lay out a system architecture, UML is used to capture the architecture of a software system development. Each diagram represents a different aspect of the architecture, the objects in that architecture, and their properties and relationships. By combining multiple diagrams and defining the relationships between them, the entire system mapping can be captured in a single shared model. [112], [113]

4.1.1.3 System Modeling Language (SysML)

As the systems engineering discipline recognized the value of using a modeling language to architect a complex system, the adoption of UML for systems engineering emerged. OMG and INCOSE began working on developing specifications for the use of UML for systems engineering in the early 2000's, and released the first specification for the Systems Modeling Language (SysML) in 2007. [112], [119]

SysML defines a method for capturing the details of a system in a set of diagrams with the relationships between each defined. Figure 4-4 shows the hierarchy and relation of these diagrams to the overall SysML model. This also shows the reuse of some diagrams from UML, and modification or addition of others for a more appropriate use of the model for systems engineering purposes.

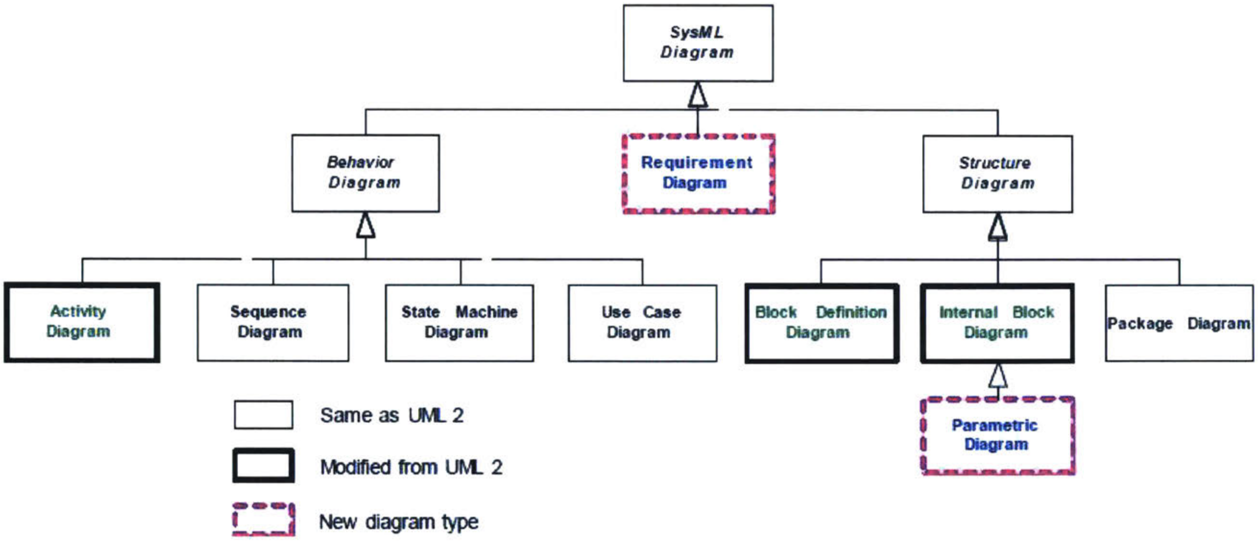


Figure 4-4. SysML Diagram Taxonomy (Source: OMG [119]*)*

The basic makeup of any diagram is by defining blocks, which can represent functional or physical attributes of the system. Blocks defining physical components may represent part of the system, such as hardware, software, personnel, or facilities. Functional blocks may represent elements such as operations or activities. Each block may have specific properties or additional parameters that describe that component, and blocks may also represent an abstraction of another diagram with additional decomposition of a component. [119]

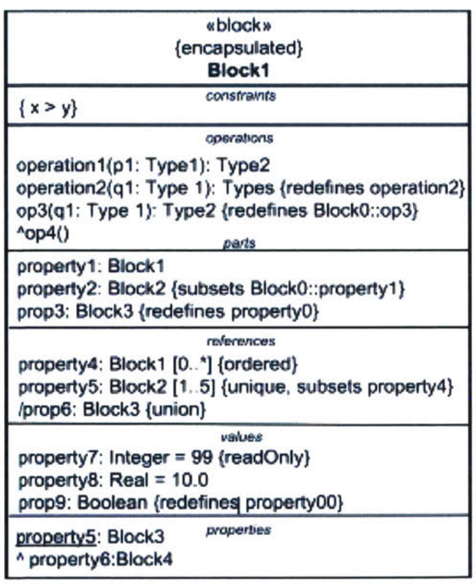


Figure 4-5. Block (Source: OMG SysML Specification [119]*)*

A diagram is a representation of an aspect of the system, which shows the relevant blocks and the relationship between those blocks, such as associations, generalizations, and dependencies. [119] Figure 4-6 shows what OMG calls the "Four Pillars" of SysML, in other words, how SysML relates the details of a system together in a manner that functionally serves the systems engineering discipline.

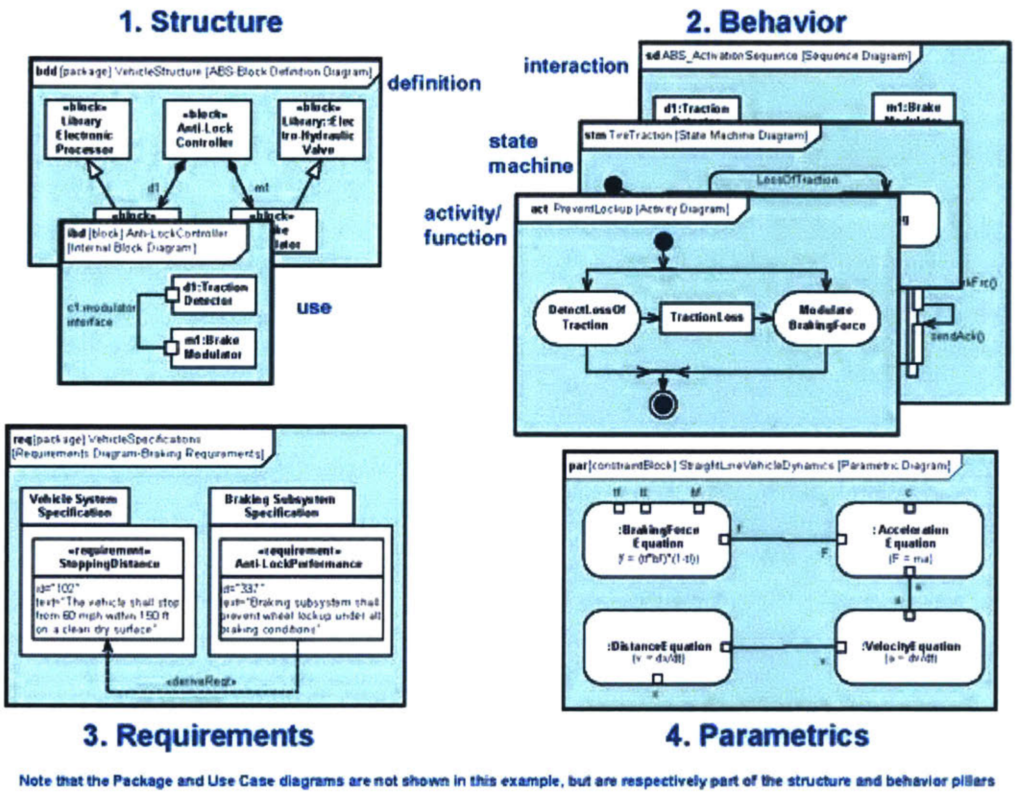


Figure 4-6. The Four Pillars of SysML (Source: OMG [120]*)*

Each of these pillars is made up of different types of diagrams, the most common of which are described in Table 4-1. A system model may include many layers of decomposition of any type of diagram. For example, there may be 3 layers of decomposition on an internal block diagram used to represent a space launch vehicle. On a high level diagram, the entire vehicle may be abstracted to a single block, which links to an internal block diagram detailing the various stages and components of the vehicle. Each of these blocks may further decompose to additional internal block diagrams that further refine the components and parts that make up the vehicle.

Key Diagram Types	
1. Structure	
Block Defintion Diagrams	• Describes the system hierarchy • Describes block properties, features, and relationships
Internal Block Diagrams	• Describes internal structure of a block- properties and connections between properties, including values, parts, and references to other blocks
Package Diagram	• Organizes the model into sets of elements that are related, but can be shared with other packages
2. Behavior	

Use Case Diagram	• High-level description of functionality that is achieved through interaction among systems or system parts by their actors to achieve a goal
Activity Diagram	• Flow of data and control between activities (can be displayed as a SwimLane Diagram to show relationship to different parts of the system)
Sequence Diagram	• Describes the flow of control between actors and systems (blocks) or between parts of a system, with time along vertical axis
State Machine Diagram	• Describes the state transitions and actions that a system or its parts perform in response to events
3. Requirements	
Requirement Diagram	• Represents text based requirements • Captures tracing of requirements hierarchy • Can be related to model elements that satisfty or verify the requirement • Bridges requirements management & model definition
4. Parametric	
Parametric Diagram	• Defines constraints on system property values (performance, reliability, mass properties) • Allows for integration of model with engineering analysis models

Table 4-1. Key Diagram Types by Pillar (Source: Modified from OMG [119], [120]*)*

A viewpoint of the model is an additional layer that can be defined, which only displays the predetermined elements of the model that will be relevant or beneficial to a specified user, in a format that will be most useful to that user or stakeholder. Artifacts can then be generated using other applications by extracting the relevant data and displaying them in a format that best communicates the information to the users or stakeholders. This could be information displayed in a table or graph, an image of a diagram for use in a power point slide or document, or any other defined method for communicating information in a method that is "expected" or easy to visualize. [119]

Although MBSE does not require the use of SysML as the method for implementation, SysML has been tightly coupled with the growth of the MBSE initiative in the system engineering culture, especially due to the close ties between OMG and INCOSE. [112] Due to the growing popularity of SysML as a method for implementing MBSE, several vendors have developed software products, sold commercially, that are based on SysML but able to interface to each other. These software solutions often integrate with other common engineering tools, including the Satellite Tool Kit (STK), MATLAB, DOORS, and other data processing or visualization tools. Most of these software tools are also being developed in compliance with the DoDAF guidance, so that DoDAF-compliant products and artifacts can be generated directly from the model, rather than requiring further data manipulation or packaging by hand.

This thesis will not review the specific tools that are available for use in the market today, but will review the use of MBSE methods that have been successful in the Aerospace industry and DoD programs.

4.1.2 MBSE Case Studies

4.1.2.1 JPL Mars 2020

After the success of the Jet Propulsion Laboratory (JPL) Martian rover, Curiosity, NASA decided to build a second rover, leveraging the previous design but upgrading the instrumentation. The Systems Engineering team for the new program, Mars2020, initiated an MBSE approach to try to solve their biggest challenges, including configuration management of data and diagrams, information silos, personnel turnover and loss of continuity, and managing multiple engineering changes to a legacy baseline. [113]

The Mars2020 SE team developed a Modeling Framework for the flight system of the new rover to document the design of the system, and produce the products and SE management through the early program development. Using SysML, all of the objects in the system architecture were captured in relationship to a series of Reference Designators. With this method, the architecture of the system could be captured at a higher level of abstraction, and details could be added as they were developed. Using a validation check, the model could also be analyzed for completeness, to ensure every interface in the Reference Model was successfully connected to another point in the model. From this centrally managed model, the team was able to export common, consistent products which were also available to the entire team via a web based interface. By combining the use of a SysML tool with a commercial visualization software, the team was then able to generate diagrams that automatically standardized all visualization parameters.

One benefit identified by this team included the ease of maintaining more consistent, up-to-date, products which allowed the SE team to focus on more challenging engineering problems. The team was also able to catch inconsistencies in the system design that they might not have caught until later in the program, arguably avoiding future redesign or rework time. The ability of the entire team to access the common model also ensured that the previous "silos" of information were eliminated, and team members could quickly access the most current design data.

One challenge that was identified on Mars2020 was that the MBSE practitioners and the flight system team members were not well versed in each other's' disciplines, and when the MBSE practitioners had moved on to other projects, the flight system team required additional training to be well versed enough to continue to maintain the model. A wiki portal was developed to share training and helpful information for the team, but ultimately an MBSE expert was required to assist the team, and both the MBSE and flight teams required training in each other's' disciplines to truly become effective.

4.1.2.2 Capabilities Based Assessment on Homeland Defense and Civil Support for NORAD

In 2009, Serco, Inc completed a Capabilities Based Assessment (CBA) on Homeland Defense and Civil Support for the North American Aerospace Defense Command (NORAD). [121] United States Northern Command (USNORTHCOM) led the CBA, which was complicated by the integration of both DoD and civil government agency participation. While a traditional DoDAF only requires one CONOPs, this CBA was developed using a UML approach to consider 13 National Planning Scenarios, such as an earthquake or Sea Launch Ballistic Missile scenario.

The team first used existing organizational documentation to develop an activity and sequence diagrams, including critical information exchanges between organizations. Task lists were developed using existing requirements, such as the DHS Target Capability List, including success criteria for each task. The structural and behavioral diagrams were then mapped to the task lists, and plugged into a animation tool to show a dynamic visualization of the scenarios. A team of stakeholders and subject-matter experts then reviewed the models and animations for accuracy and completeness.

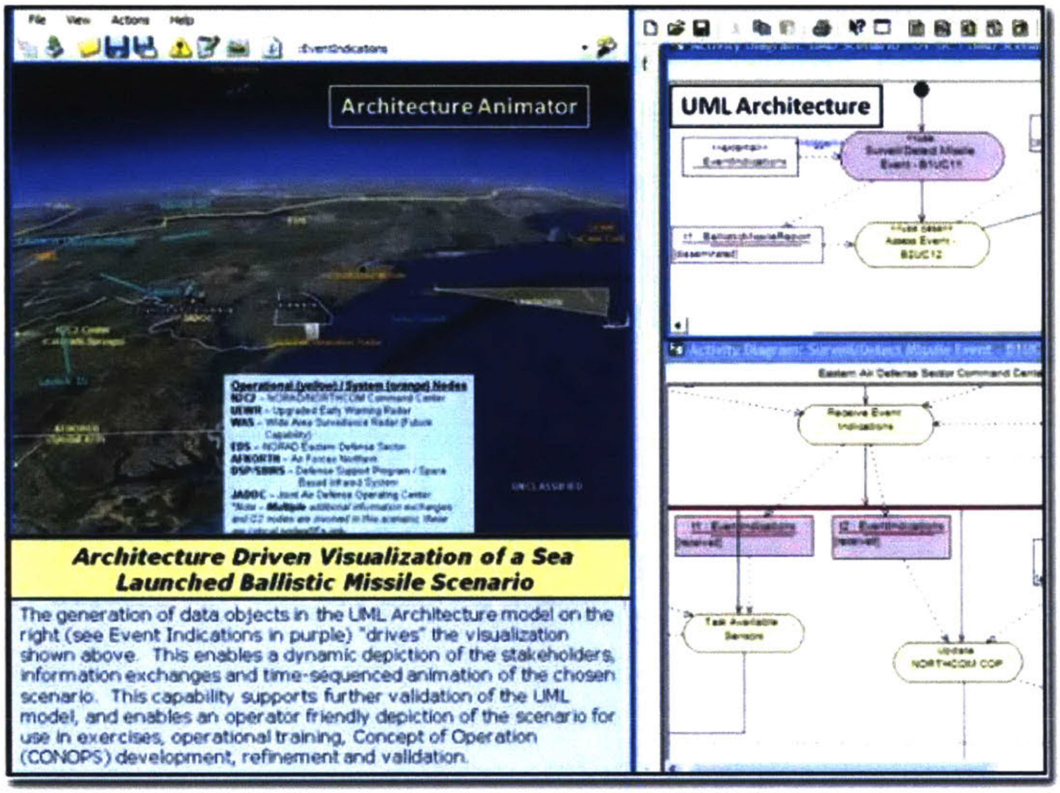


Figure 4-7. Developing a Dynamic Scenario Animation "Driven" by the UML Architecture (Source: Serco [121]*)*

This process allowed a collaborative review of the entire process, including verification of the documented data exchanges and component requirements, and a better understanding of the entire scenario response by all stakeholders. Finally, this allowed the subject matter experts (SMEs) a thorough process to identify capability gaps in the process, whether they were due to info sharing, doctrine, policy, or material needs.

Figure 4-8 shows an activity diagram for the Sea Launched Ballistic Missile scenario, where the activities are designated to various stakeholders via swim lanes (shaded columns in the background of the image). The text box with the red text details a DoD capability gap that was identified through this process, and the blue text below captures the recommended mitigations that could be considered for this gap. The team was able to identify one policy and one information sharing recommendation that would help close the gap, and clearly articulate what gap remained for consideration in a future system AoA for a material solution.

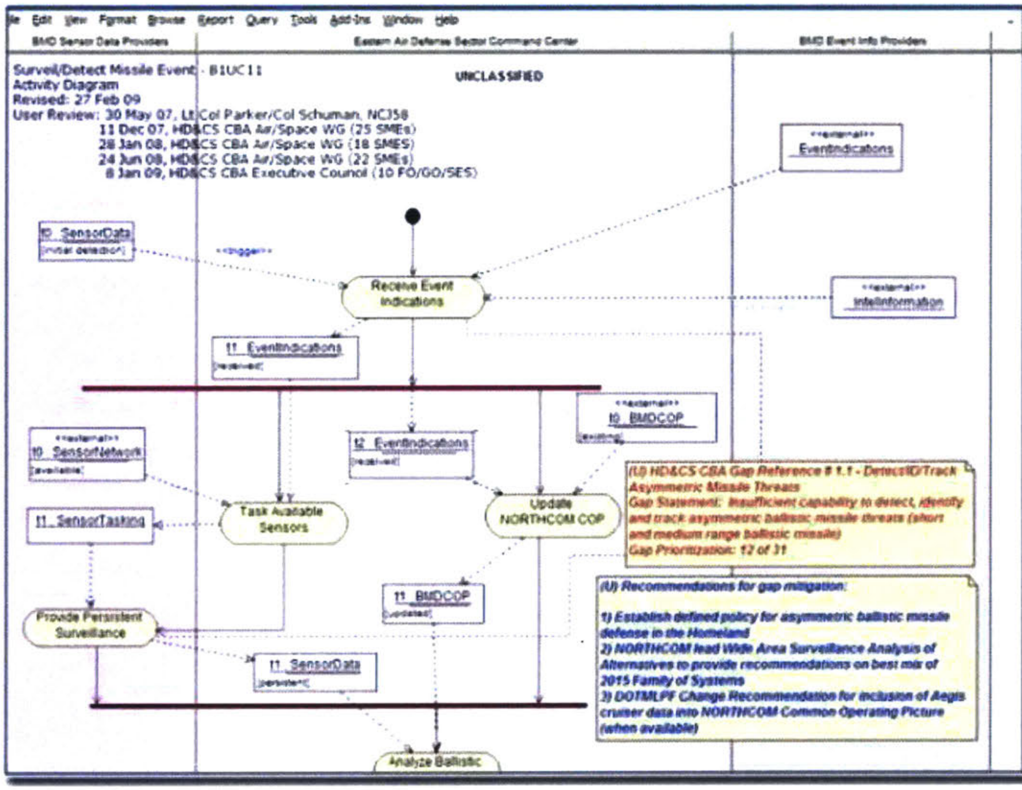


Figure 4-8. Scenario Gap Analysis (Source: Serco [121]*)*

The products from this CBA, including various scenario diagrams, a clearly understood list of capability gaps, and an animated visualization of each scenario were then made available for each of the participants. These products could then be used for defending budget requests, identifying better response processes, and assisting senior leaders with articulating the actions and responses for their agency. At the time of publication, the team also anticipated that these products could be used for the development of a common operating procedure and common data exchange formatting, as well as future training and exercise planning.

4.1.2.3 MILSATCOM MBSE Application

The Military Satellite Communications Directorate (MILSATCOM) is the organization responsible for the acquisition and integration of satellites, terminals, and control stations for the DoD's protected and wideband satellite communications. This highly complex system is critical to the Nation's warfighting capabilities, but is highly disputed when it comes to the acquisition strategy for future systems. [122]

LinQuest Corp, who provides engineering support to MILSATCOM, has developed an MBSE approach to aid in the future systems engineering efforts for several components of the MILSATCOM ground and terminal systems. By using several tools, including a SysML MBSE tool, and DOORS for requirements management, this team has developed an integrated system model that supports all phases of the Systems Engineering "V" for these programs, as can be seen in Figure 4-9.

Figure 4-9. MILSATCOM MBSE Application: Supports All Phases of Systems Engineering Vee (Source: MILSATCOM Program Office)

This MBSE tool captures a total of 5 Technical Requirements Documents (TRDs) for the management of two FFRDC-developed components, one contractor-developed component, and one component that will soon be competed for development by a defense contractor. The fifth TRD is a system-level document that integrates the various components.

The process for developing this model began with a team of subject matter experts and MBSE facilitators that took the JCIDS-developed CDD capability requirements for the system, and began developing thorough use cases. Each use case was captured in SysML through functional diagrams, which defined the start-to-finish required capabilities and tasks for the system. Once the use cases were well understood, each function or task was further defined as a TRD-level system requirement, and delegated to a "swim lane," or model for a specific component. The interfaces between each task, component, and external relationships were captured as information exchange requirements, which were then used to generate Interface Control Documents (ICDs) complete with the exchange details, or properties, clearly defined.

For external consumption, the TRDs for each component can be auto-generated directly from the model, to ensure it captures the most recent configuration. Additionally, the diagrams capturing the system descriptions are DoDAF-compliant, and can be auto-generated for incorporation in any product.

Through the use of this MBSE model, the team has captured both functional requirements and structural tracing all the way back to the CDD, and is now expanding the capabilities of the model for future use. For example, each requirement identified in the TRD is tracked with a Requirement ID, but from a verification and test perspective, is also translated into a Verification ID. The previous use cases have also been translated directly into test use cases, and each Verification ID is linked to a master schedule that projects when that ID will be verified. The test procedures can also be auto-generated with diagrams showing proper system configurations for each step, diagrams showing the flow of the steps, and specific step descriptions, instructions, and success criteria.

The MILSATCOM MBSE application has been developed to support all phases of the systems engineering "V" model, and is compatible with other SysML tools used by the FFRDC and contractors doing the development work. This model was used to facilitate the collaboration between all stakeholders in the use case and requirements development, and can be reused for all future work on the system. It provides a centralized configuration management capability that is easily accessible through a web-based interface, and ultimately allows for a more thorough and effective development of future systems. This model will also streamline the change management process, because it integrates the requirements for several different systems, developed by different vendors. The systems engineering team performing the integration will be able to quickly and easily identify how a change in one system will impact the other systems, and demonstrate the impact through the model to all users.

It should be pointed out that this model is not the end-all be-all for the MILSATCOM directorate. MILSATCOM has several other extensive modeling capabilities that are used to analyze the performance of the current communications architecture world-wide, to predict impacts of threats and gaps, and for future space and terminal acquisition planning. Tools like these are incredibly comprehensive, and will likely never be replaced by the MBSE modeling architecture described previously. This new MBSE approach has proven, however, that there is a valuable potential for models to replace previous document-based systems engineering functions.

4.2 Portfolio Management

Using MBSE for R&D portfolio management requires understanding what makes project portfolio management effective. This is a well-researched and documented topic, Wicht and Szajnfarber provide a comprehensive review of the many portfolio management methods that might be most applicable for the management of large space R&D portfolios. [123] This article also highlights the four considerations that make portfolio planning for space R&D a challenge, and different from typical technology investing. First, it is difficult to define a value proposition for government projects, where the standard industry measurement is return on investment. Second, the number of technology changes in a single large program in each generation of its release can be very high, particularly when there are multiple subsystems or components that are all maturing for both government and commercial purposes. Third, is the long development process inherent in government programs from the time of investment to the time of operational use. And finally, because the government relies on civilian contractors for the development and production of most operational systems, there are industrial base considerations that must be weighed for long term industry viability. [123] These four factors greatly influence how the DoD make decisions about R&D projects, and must be considered carefully when examining the best portfolio management approach.

Project methods of investment decision making are used to select a project from a set of projects that are being judged for best value, but without consideration of their interdependencies. Project methods can be generally grouped into four categories- non-quantitative, scoring, comparative, and cash flow methods. Each of these categories have several different methods for achieving the decision making process, and each may be appropriate depending on the size and scope of the project, and the environment in which the decisions are being made. The biggest shortfall, however, is that these methods do not capture the interdependencies between projects or technologies, and thus they may fail to recognize inherent risk in similar approaches within a set of projects. If all projects are reliant on one specific advancement in a technology component, and that fails to materialize, then the entire portfolio for that area could fail. Strong risk management requires a deliberately diverse investment in different methods or approaches to achieving a capability need. [123]

Portfolio management, on the other hand, is intended to look at a set of projects that may be complementary to each other, and in total, best meet the strategic objective. [124] Again, [123] summarizes these into three broad categories- qualitative, quantitative, and optimization portfolio methods. Within each of these categories, there are several distinct methods that are commonly used and written about. This article concludes that there is no single solution that will likely meet the needs of a complex space R&D agency, but that a combination of tools may be necessary.

An MBSE approach can easily provide the backbone structure necessary to integrate several of these portfolio management approaches so that senior DoD decision makers can make more structured, strategic decisions. First, it must be understood that MBSE will provide the means to gather the appropriate data from both stakeholders, to capture their intent and objectives, and R&D providers, to capture the data about their proposed projects. The following sections will address different aspects of portfolio management that will be incorporated in the recommendation of this thesis. The specific implementation will be discussed in Chapter 5.

4.2.1 Roadmapping

Technological roadmapping can occur for different purposes, and at varying levels of detail, but ultimately are meant to represent, "a graphical representation of technologies, often relating objects like products or competencies and the connections that have evolved between them in the course of time." [125] Roadmapping has advanced in recent years, from basic lines on a chart marked by key milestones, to advanced software tools able to capture and communicate information, link roadmaps across boundaries and organizations, and tie scenario planning to future technology needs.

[126] describes roadmapping as a means to link technological resources with company objectives, which requires linking multiple technology management processes from different disciplines of the business. Roadmapping can also lead to improved coordination, collaboration, and cooperation of entities within or between organizations. [127] In this context, coordination is intended to harmonize activities between multiple entities, to avoid gaps or overlap. Collaboration is looking at a problem from a systems view, and delegating portions to different organizations that must work together to achieve the shared objective. Cooperation describes an environment where multiple entities are working independently, but linked toward a common objective. This objective may be jointly defined, but as each entity evolves and progresses, the environment in which the system operates may evolve as well. One example of this cooperation is the shift towards open innovation, where platforms and developers are evolving concurrently. Figure 4-10 displays these three concepts that can each be improved with technology roadmapping.

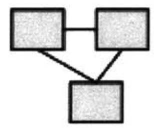
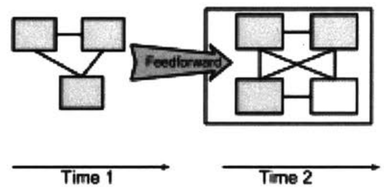
	Coordination	Collaboration	Cooperation
Structure			
Agents	Dyads	Network	Ecosystem
Purpose	Task harmonization	Translation of shared goals into individual agent articulation of objectives and activities to facilitate co-creation	Strategic initiatives within and between agents to create value and proactively influence strategic future space

Figure 4-10. The Interaction Continuum (Source: Technology Management [127]*)*

One advantage of roadmapping versus other portfolio management tools, is the ability to communicate to others, both internally and externally, specific capabilities and timelines to achieve this coordination, collaboration, and cooperation. [125] In the DoD, this is a valuable method for achieving stakeholder buy-in on the future paths forward, communicating those intentions to a broad audience, and defending investment decisions to external stakeholders, such as Congress. Specifically, Chapter 5 will examine how we can use MBSE tools to conduct roadmapping, and achieve coordination of the pre-acquisition processes, collaboration amongst all R&D entities, and cooperation between the government, external stakeholders, and industry.

Today, basic roadmapping efforts are occurring through the space enterprise, but none at the enterprise, cross-functional level. For example, AFSPC and the Space Superiority Systems Directorate (SMC/SY) are working on developing a roadmap for space situational awareness, including the sensors owned by the space surveillance network. Although a commendable effort, this is still being completed by linking Microsoft Project data together to create a schedule with milestones, and other data in document formats to support. Although it provides a means for collaboration and communication, it is still a manpower-intensive, human driven and analyzed tool that requires human verification for accuracy.

Another example is the Overhead Persistent Infrared (OPIR) mission area plan that Congress directed be conducted in the 2013 National Defense Authorizations Act. This required a strategy, plan, and budget, coordinated between the DoD and Intelligence Community, for the entire mission area. This plan was delivered in October 2013, and included this information for the current and next generation of systems, including the technology needs for advancement. [128]

Again, this is an excellent start to a comprehensive roadmapping function, but completed only within the OPIR mission area. AFSPC is building an architecting group to expand this roadmapping function, and we will discuss in Chapter 5 how MBSE could be used by this group. [90], [104]

4.2.2 Strategic Bucketing

Another qualitative portfolio method discussed in [123] is strategic bucketing, which is distributing investments into general funding allocations without consideration of specific projects. We do this in many ways in the DoD today, and in fact it is the most common method of "portfolio management" used for R&D in the DoD. First, we distribute funding to various organizations, such as DARPA, the FFRDC's, and the labs. Then, we mandate that certain percentages of some of this funding be designate for basic and applied research, although we do not dictate at the DoD level which mission areas or types of technologies this must be used for. Finally, each organization often does its own strategic bucketing amongst the directorates or 2nd level organizations, where it is more directly tied to mission areas. As discussed in Chapter 3, each of these organizations has a different method for then deciding the project method used to make funding decisions, and how they tie those decisions to strategic objectives.

Strategic bucketing, or "peanut butter spreading" is useful when the future objective or most likely outcome is unclear, and a minimum capability should be maintained in multiple areas. The drawback, however, is that it lacks a specific tie to future desired objectives, and prioritizations are generally only made within a specific area of research, versus across the entire portfolio. It also discourages collaboration more than other methods, because the funding streams are often managed in a silo, versus across technology areas.

4.2.3 Optimization Methods

There are several different methods that fall into the optimization category, but summarily, they all evaluate the available data for each project for the optimal combination of projects to meet the prioritized objectives set by the organization. This may involve analyzing a specific set of parameters, it could be directed at achieving a specific set of goals in priority order, or it could be focused on specific success criteria. In many cases, tools can be developed to analyze a set of data provided in the predetermined format, and algorithms can be run to ascertain the ideal set of projects within given constraints. [123]

4.3 Design Structure Matrix

One tool that can be used to capture the relationships of system is the Design Structure Matrix (DSM). DSM's can be used to define the relationships between elements of a product architecture, organizational architecture, process architecture, or a combination of these. In a very simple example, Figure 4-11 shows how a simple system can be decomposed to depict a lower level of detail. In (a), the system is decomposed using a standard tree diagram, as is commonly used in the DoD. (B) shows how this diagram is represented at the first level of decomposition in a DSM, where an x in the box correlates to a relationship between two elements. (C) shows this mapping of relationships at the second level of decomposition. The colored boxes highlight how the system is currently organized, despite the x's outside these boxes. The extraneous x's highlight that there are cross-element relationships that may be more difficult to identify or maintain due to the current system's boundaries. [129]

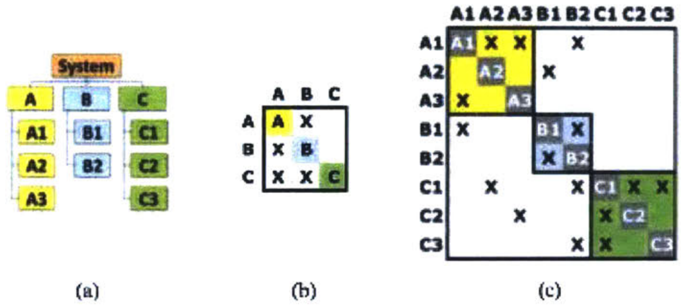


Figure 4-11. Decomposition of a system in (a) a tree diagram, (b) a high level DSM, and (c) a low level DSM (Source: Design Structure Matrix Methods and Applications [129]*)*

Figure 4-12 shows a method of decomposing a product architecture, by taking a typical block diagram and turning it into a DSM. In this DSM, there are 4 colored boxes that represent each relationship, rather than a single x as seen in the previous example. This allows for an additional level of detail to describe the types of relationships, including physical connections, mass flows, energy flows, and informational flows. [130]

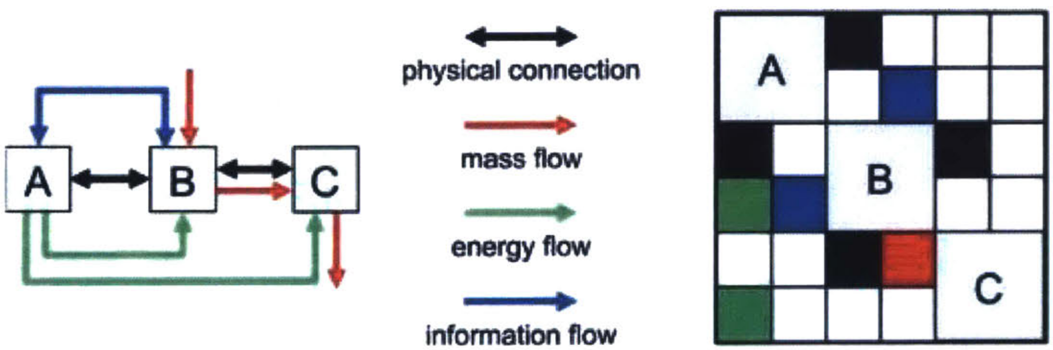


Figure 4-12. Block diagram (left) and corresponding DSM (right) of a simple system. (Source: Xerox Example [130]*)*

This method was used to analyze the architecture of a Xerox digital printing system with 84 components. The component numbers line the vertical and horizontal axis, and the relationships between each component are captured using the 4-colored scheme described above. The yellow boxes around each set of squares represents how the system was organized into nine subsystems.

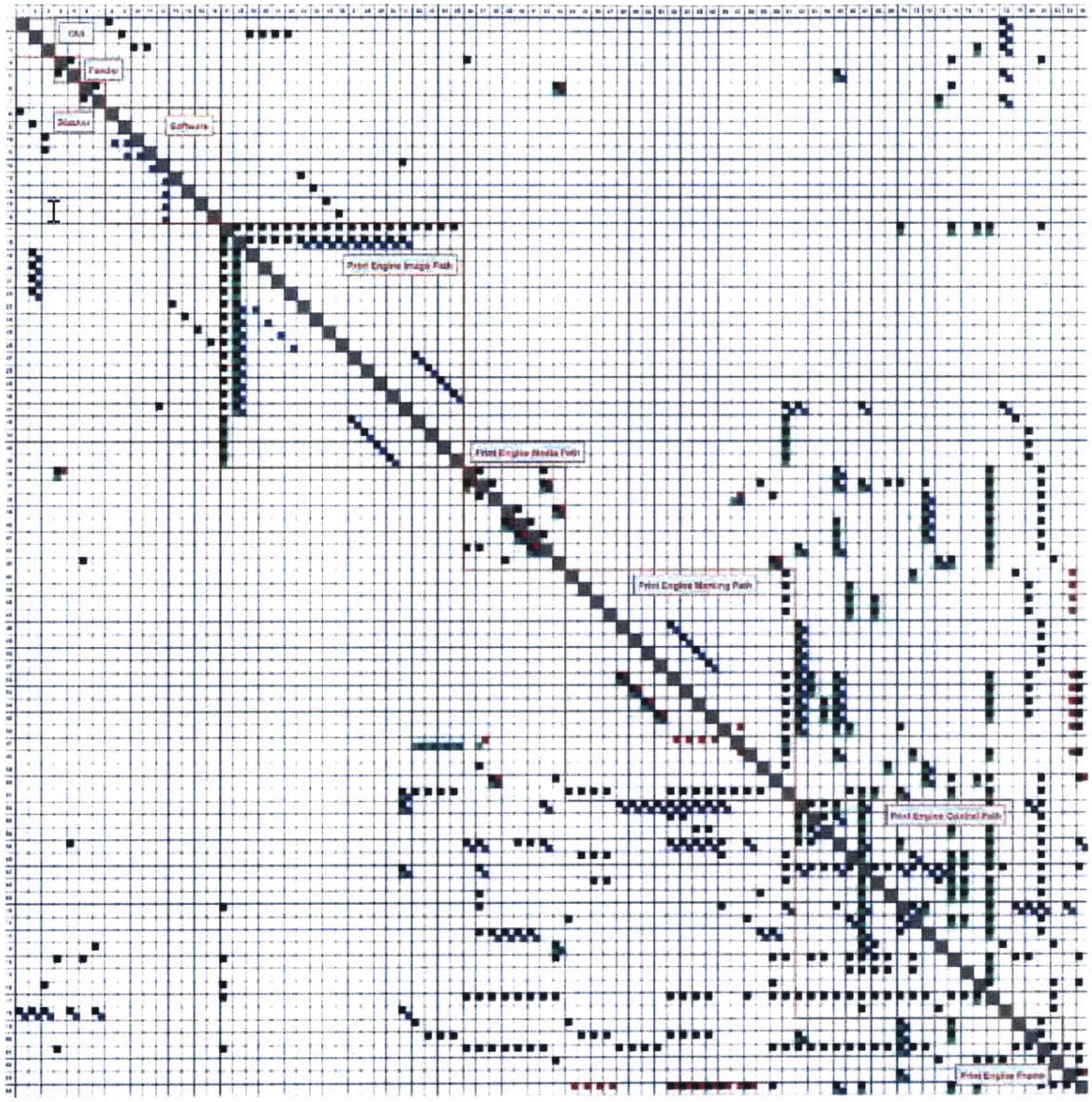


Figure 4-13. Product architecture DSM of the Xerox iGen3 digital printing system, indicating four types of interfaces across the 84 components, grouped into nine subsystems. (Source: Xerox Example [130]*)*

By analyzing an architecture using the DSM method, we can capture the relationships between elements and analyze them for several purposes. By conducting a DSM on a product architecture, we can draw conclusions about work flow, dependencies, proper segmentation for the subsystems, and many others. This can also be used to make decisions about design changes, future modularity, and other design decisions that rely on understanding the connectivity of a system. [129]

The same method can be used to analyze organizational architectures and process architectures. In an organizational DSM, we might learn whether our teams are effectively organized depending on who they must communicated with most regularly. In a process DSM, we can identify what information, products, or services are required between all the steps in the process. This can help us distribute work, better align work flows, develop schedules, and identify potential gaps or overlap in the process that could be eliminated.

4.4 Challenges and Benefits

4.4.1 Challenges with Implementation

After interviews with several teams and experts using MBSE, the following challenges with implementing MBSE are summarized: [75], [86], [91], [103]

Start Small, Expand Where Valuable: Every team interviewed cautioned against trying to take on too large a scope with an initial MBSE project. Each recommended that any MBSE project undertaken should begin with a small focus area, to develop the team's acumen with the tools, and to show value in the approach. Once the ontology and methods are well understood, the work done initially can often be reused for expanded capabilities, as long as discipline is maintained between architects using the model. This also requires a firm change management process to ensure components are kept up-to-date, but important information is never lost.

In another application of MBSE used by JPL, approximately 40 team members are using MBSE to develop a shared system model for the development of a new spacecraft. Although they are in the early stages of developing this capability, they reported some initial lessons learned in an MIT lecture to the System Design and Management Program. They conceded that culture change is hard, and "evolution not revolution" is critical with regards to linking the model back to existing processes. A complete disruption of the existing business processes is sure to meet resistance, and will make adoption much more difficult. A more successful approach is to build on existing processes that can be bolstered by the new capabilities, and gradually replace those that become obsolete. [111]

Most teams also warned against trying to create a single, massive model to solve all problems. They highlighted that uninformed visionaries often get carried away with the scope of capabilities they want the model to facilitate, without a realistic understanding of the cost, schedule, or complexity of such a model. Anecdotal references to previous failed attempts in and out of the DoD cited the burgeoning up-front costs that were proposed to the government, due to the cost to transfer existing or legacy systems to the new approach. A more realistic path to implementation is to demonstrate the approach that will be used in a pathfinder program, and once the methods are understood, require that future efforts follow the new approach. [43], [86], [91] Teams may find some benefit to modeling legacy systems at an abstracted level, but the focus should be forward-looking on future applications.

Clear Objectives: As with any new project, it is important that the MBSE developers understand the purpose for which the model is being developed, and it is critical that the project experts understand what the tools can and cannot do. By combining a team of mission area SMEs and MBSE practitioners, a clear set of inputs and outputs for the approach can be developed and scoped to best fit the intended purpose. [91], [103] One JPL team highlighted that improving communication must be upheld as the most important objective of going to an MBSE architecture development strategy. [111] This is important, because enacting an MBSE approach will cost time, money, and resources, and the objective should be focused on improving the systems engineering processes that make a program successful. MBSE should be seen not as a solution for all decision making, but as a tool that supports decision making.

Focus on the Customers: After a recent trip to Silicon Valley, there was one driving focus that was consistent across every company. Tesla, Apple, Google, C3 Internet of Things, the Visa Innovation Center, Amazon, Gallo Wineries, Intel, and Planet Labs are all laser-focuses on the customer, and what will sell their products. Google calls this the "user experience," and recognizes that launching a poor product will lose customers' trust. Tesla will not consider any new features in a vehicle that haven't successfully been demonstrated in a test vehicle as simple, easy to understand, and easy to use. [131]

Using Silicon Valley's measure of success, any new effort to roll out an MBSE approach must be focused on the decision makers, and the information they need to make well-informed decisions. Products created from the model must be clear and accurate, and must provide a better quality of data or analysis from what was available previously. The underlying method and assumptions must be easily explained and understood, so that decision makers do not focus on the "how" as much as the "what."

Cost: There will be cost associated with the new implementation of an MBSE method. The teams interviewed had several cautionary recommendations with this regard. First, it is difficult to capture a cost savings associated with a project like this, because we are attempting to integrate the complexities and interfaces that have never before been adequately managed. The costs of developing a new capability will need to be weighed against the cost of doing business today, and the lost opportunity costs from the inefficient processes used for R&D decision making today.

Classification: The biggest challenge, which is unique to the DoD from any of the case studies examined, is maintaining a usable MBSE approach at the appropriate classification levels. Although much of the space R&D work today is done at an unclassified level, this work can become more sensitive as it is aggregated into comprehensive assessments and functional capabilities. Additionally, although our high-level future priorities are communicated openly to the public, we may be less inclined to share the specific desired future technology capabilities in an open manner.

The benefit of using an MBSE approach is that various "layers" of the model can be maintained at different classification levels, and ingested into higher classification models for advanced aggregation or analysis. Additionally, access to various portions of the model can be partitioned so that only specified users have access to specific data. The specific implementation of this security concern will be discussed in more depth throughout the recommendation section of this thesis.

4.4.2 Benefits

Despite the challenges of implementing an MBSE approach for improving our decision making in the DoD, there are many potential benefits.

Communication: More than any other benefit, the use of MBSE will provide a means for improving communication amongst all stakeholders, and enabling access to a product that enhances knowledge for all decision makers. By capturing the information in a shared model, we improve consistency, accuracy, and clear assumptions for critical analyses and decision making across the Department. [132]

Centralized control, decentralized execution: The first tenet of airpower, as captured in US Air Force Doctrine, is the concept of centralized control and decentralized execution. [133] Centralized control is the intent of giving strategic vision and planning to a higher level decision maker, and then allowing the tactical commander to execute the orders and guidance they have been given. [134] In order to do this, the strategic decision makers must have a clear understanding of the battlefield.

In the case of space R&D, we do not currently have a clear strategic decision maker capable of making DoD-level decision, because no one has a full understanding of the space enterprise and its dependencies. By implementing an MBSE approach, we can create a data-driven understanding of the dependencies across mission areas, the overlap in capability needs between mission areas, and ultimately a roadmap that displays strong systems engineering and analysis to support budget requests and plan future technology development. MBSE will also allow for a consistent, central repository of the most up-to-date information, so that users can quickly access the data and understand the assumptions behind it.

The DoD Space Enterprise has an inherent decentralized execution framework, as described in Chapter 3, with the sheer number of entities doing R&D work for space systems. If we can guide the funding and priorities of each of these organizations in a fair, organized way, then the organizations can focus on executing their research. As one R&D portfolio manager recently quipped in a personal interview, "Researchers are generally good at managing, proposal writing, or conducting the research. But never all three. It's hard to build a team that balances those capabilities, when all they really want to do is research!" If we can transition the proposal and documentation work away from paper, and allow the engineers and researchers to document their work in a model template, we have created a functional tool that can be used by both organizations.

Optimized Decision Making: As described in Chapter 3, the DoD funds R&D through a myriad of diverse entities and methods. The existing system is not being managed at a portfolio-level today. This thesis does not recommend a specific approach to portfolio management decision making, but outlines how an MBSE approach can be used to collect the data necessary to make smart strategic portfolio investment decisions. By aggregating the data for projects meeting specific capability needs across the DoD, our strategic decision makers can better balance the cost, schedule, performance, and risk in each mission area for future technology development. With this method, deliberate duplication of objectives achieved across diverse methods and organizations will better align the space enterprise and enable more rapid technology growth.

Understanding Dependencies and Synergies: As our world becomes more complex and interrelated, we must understand the dependencies across our systems. Understanding these dependencies will help us prioritize our investments, and may help us find efficiencies or new applications of technology that was previously being developed for a different mission area. Emergent from an integrated mission model will also be synergies in functional and technical capabilities that will help us operate and make us better warfighters.

Open-Systems Architecture: The potential value of an open-system architecture has been speculated and encouraged, but is difficult to do in practice unless the interfaces between systems are clearly defined and common exchange requirements established. An MBSE approach to modeling the future desired systems will inherently define those interfaces as part of the model, which potentially allows for more modular, open system development. If future acquisitions continue down this modular approach, then MBSE becomes critical to change management across related systems, where the impact of a change in one component or piece of the system can be quickly and accurately ascertained across the entire system. [109]

Coordination: Across the pre-acquisition process, there are many cascading but not always aligned efforts at capability gap assessments, roadmapping, setting priorities, investment planning, and decision making. Each step of this process happens in multiple organizations without consistent coordination. MBSE will not solve our human problem of socializing the information with the right people. However, Chapter 5 suggests how the appropriate organizations can work together, using MBSE as a tool to facilitate the process, which each organization can then access and analyze at the appropriate level of abstraction as is necessary for their needs. Multiple viewpoints in the model can support users from different parts of the DoD, and consistent DoDAF artifacts can be produced for various purposes.

Collaboration: The recent guidance from Gen Hyten and AFSPC regarding space priorities in the future has been well communicated to those in AFSPC and AF-related organizations. [4], [93] But how well are we aligned with the Navy? How well is DARPA trying to meet those objectives? Has this helped industry plan their R&D investments for the next 5-10 years, or are they still blanketing the Pentagon trying to ascertain the best focus for their dollars to gain a competitive edge in upcoming acquisition selections? If we can develop a releasable model that clearly communicates our intentions, as well as a roadmap for the planned acquisition programs that shows a time-based need for the development of the capabilities, we can better align the entire community with our priorities. For example, if we communicate transparently to all R&D entities that we will be funding 5 launch opportunities for technology demonstration for priorities 2, 4, 5, 6, and 8 in 20xx, then we are setting clear expectations and funding opportunities for those priorities. Further, if these demonstration opportunities precede a clear technology on-ramp or AoA for the next generation, we have provided incentive to meet schedule needs and technology objectives.

Cooperation: The R&D process operates inside other DoD processes, such as JCIDS and the PPBE processes described in Chapter 3. This MBSE approach will create better communication products, and a better aligned portfolio that will please stakeholders in both the JCIDS requirements and PPBE funding processes. Additionally, one of the DoD's biggest stakeholders is Congress, who much be convinced annually of the justification for spending and decision making within the Department. A well-developed plan that is easily communicated to Congress allows for a more effective feedback loop during budget reviews, and usually leads to a more robustly funded budget. Most Congressional reductions to programs do not stem from a disagreement over the program itself, but from a lack of ability to communicate the appropriate information that gives Congress confidence in our ability to execute the program.

Existing Methods and Tools: Although the use of MBSE has grown over the last decade, there are already several compatible software tools and suites, particularly based on the SysML method, available as commercial products. Additionally, many of these tools have existing interface capability to run additional analysis and simulation using well-known software such as MATLAB and Satellite Tool Kit. The DoD has greater chance of the adoption of an MBSE approach if the stakeholders have options regarding which tools they use, versus selecting one tool and forcing stakeholder to pay for licenses. Additionally, the more open the software architecture is for interface with other types of software tools, the better connected the model can be.

Chapter 5 Recommendations

5.1 Streamlined Pre-Acquisition Process Using Various Tools

Chapter 3 described the many existing functions within the pre-acquisition process (PAP) for space R&D, which have adapted and emerged over time into what they are today. After analysis of the entire conglomeration of functions that exist, it appears there is a single, streamlined series of functions that could complete the pre-acquisition process if a clear governance structure is established, and participation from all of the key stakeholders is welcomed and included through the use of improved methods and tools.

This recommendation to improve the PAP combines the use of SysML and an MBSE approach, the use of technology roadmapping, and the use of Design Structure Matrices to develop a model that can integrate the various steps in the PAP and can integrate the technical needs across mission areas to help the DoD manage the complex R&D environment for the DoD Space Enterprise.

This PAP, as summarized in Figure 5-1, incorporates all of the functions that exist currently, but linearizes them into a single flow with cooperative participation. This diagram also identifies the high-level inputs and outputs required for each function of the process.

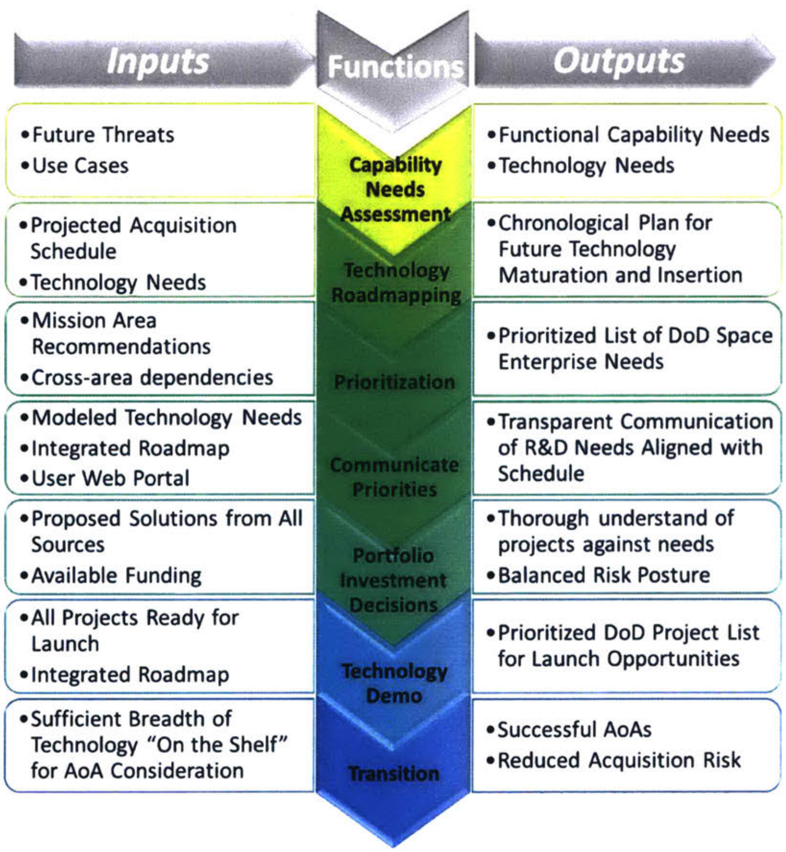


Figure 5-1. Streamlined Pre-Acquisition Process for R&D in the DoD Space Enterprise

As the enterprise exists today, many of these processes are duplicative and occur in various organizations and at various levels of the enterprise. Table 5-1 does not distinguish between roles, but does show all the participants in the process today. It is difficult to assign a single owner to any of these functions in the structure today. The red "x's" show the intention to do these functions, but it is not cohesively being performed yet.

Participants in R&D Functions Today

		Capability Needs Assessment	Technology Roadmapping	Prioritization	Communicate Priorities & Roadmap	Portfolio Investment Decisions	Technology Demo	Transition
Acquisitions	PDSA Staff	X		X	X	X	X	X
Acquisitions	JCIDS FCBs	X		X	X	X		X
Acquisitions	PPBE (HQ staffs; CAPE)	X		X	X	X		X
Acquisitions	DAS (SAF/AQ; OSD/AT&L)	X					X	X
R&D/ Pre-Acquisitions	ASD(R&E) (ExCom/COI)	X	X	X	X	X	X	X
R&D/ Pre-Acquisitions	USSTRATCOM (JFCC Space)	X		X				X
R&D/ Pre-Acquisitions	AFSPC (A5/Chief Architect)	X	X	X	X	X	X	X
R&D/ Pre-Acquisitions	SMC, ONR (SMC/AD)	X	X	X	X	X	X	X
R&D/ Pre-Acquisitions	SPOs (Varies)	X	X		X	X	X	X
R&D/ Pre-Acquisitions	R&D Entities (Labs, FFRDC, DARPA, etc)	X		X	X	X	X	X
R&D/ Pre-Acquisitions	Industry							X

Many Participants;
No clear owner or collaborative processes for these functions today

Table 5-1. DoD Participants in Space R&D Functions Today

In this proposed PAP, each of these functions should have a single owner. There may be many participants, but there should never be duplicative functions unless intentionally delegated or divided.

Streamlined Roles & Responsibilities

		Capability Needs Assessment	Technology Roadmapping	Prioritization	Communicate Priorities	Portfolio Investment Decisions	Technology Demo	Transition
Acquisitions	PDSA Staff	Chair	Approval	Approval	Chair	Chair	Chair	Oversight
	JCIDS FCBs	Support	Support	Support	Receive Info	Support		Support
	PPBE (HQ staffs; CAPE)		Support		Receive Info	Support		Support
	DAS (SAF/AQ; OSD/AT&L)		Support		Receive Info	Support	Support	EA
R&D/ Pre-Acquisitions	ASD(R&E) (ExCom/COI)	Support		Support	Receive Info	Support	Support	
	USSTRATCOM (JFCC Space)	Support		Support	Receive Info			
	AFSPC (A5/Chief Architect)	EA	EA	EA	EA	EA	EA	
	SMC, ONR (SMC/AD)	Support	Support	Support	Receive Info	Support	Support	Support
	SPOs (Varies)	Support	Support	Support	Receive Info	Support	Support	Support
	R&D Entities (Labs, FFRDC, DARPA, etc)	Support	Support	Support	Receive Info	Support	Submit	Support
	Industry				Receive Info	Support	Submit	Support

Table 5-2. Summary of Roles & Responsibilities under Streamlined PAP (Source: Kate Cantu)

As seen in Table 5-2, for most of these functions, AFSPC is proposed to be the executive agent (EA) to execute the process required for that function. Within AFSPC, a Chief Architect role should be clearly formulated to own and execute each of the functions described here. Several of these functions would require participation and collaboration across the community, and although the AFSPC/CA would facilitate the process, the chair of the governance boards would be the PDSA. This is critical, because although AFSPC is the CFLI and responsible for leading the development planning process for space superiority, AFPSC does not have the authority to drive decision making in the other Services. The PDSA has been directed to, "oversee all departmental space matters, including policies, strategies, plans, programming, and architecture assessment across the DoD Space Enterprise," and as such, has a greater authority for chairing each of the functions described in this recommendation. [26]

Although the Air Force would continue to lead the space enterprise work, it is critical that proper participation from the other Services and government entities is included, to truly make this an integrated DoD level product.

In the following sections, this recommended streamlined approach is described, including how an MBSE approach and other tools can be used to facilitate these functions.

5.1.1 Capability Needs Assessment

The first function in the PAP is to conduct a capabilities needs assessment (CNA) for the desired functional capabilities for each mission area at an end state that is at least 15-20 year in the future. Senior leadership from AFSPC recently highlighted in a personal interview that we need to think 1-2 generations beyond what is already being planned, so that we can adequately invest in technologies with enough time to develop and demonstrate their capabilities. [90] The ideal end state for this CNA would encompass the time period in which all mission areas would need a Next Generation +1 or +2 acquisition solution. In most mission areas today, we are procuring or beginning to procure the next generation of the constellation or system beyond what is already on orbit.

This process, would begin with a team of MBSE practitioners facilitating the CNA working group for a single mission area. This working group would be chaired by the PDSA staff, as the unifying authority for the DoD Space Enterprise. The Executive Agent for the architecting function, and for facilitating the working group would be the AFSPC Chief Architect (AFSPC/CA). Participating membership in the CNA would include each of the organizations identified in **Error! Reference source not found.** at a minimum.

Today, there are many different efforts trying to conduct future architecture development and gap analysis, in a very stovepiped method. This new function would replace those independent efforts and combine them into one focused process. Many of the participants may conduct independent analysis to support this central effort, but ultimately, it would conducted and documented centrally in the process described below, through collaborative participation of all the key stakeholders.

Figure 5-2 outlines the CNA process, for an example mission area. In this example, the Space Protection mission area is examined, which crossed three main functional components- Space Situational Awareness (SSA), Defensive Counterspace (DCS), and Offensive Counterspace (OCS).

	Stakeholders	Capability Needs Assessment	*R&R Definition*
Acquisition	**PDSA Staff**	*Chair*	Makes final recommendations to DepSecDef
	JCIDS FCBs	*Support*	Represents CCMD capability needs
	PPBE (HQ staffs; CAPE)		
	DAS (SAF/AQ; OSD/AT&L)		
Pre-Acquisition	**ASD(R&E)** (ExCom/COI)	*Support*	Provides expertise from technical subgroups with S&T perspective
	USSTRATCOM (JFCC Space)	*Support*	Provides space warfighter perspective
	AFSPC (A5/Chief Architect)	*EA*	Executive Agent- Facilitates MBSE approach and working group execution
	SMC, ONR (SMC/AD)	*Support*	Provides integration support for entire process across all mission areas
	SPOs (Varies)	*Support*	SMEs from appropriate mission area provide technical and acquisition knowledge
	R&D Entities (Labs, FFRDC, DARPA, etc)	*Support*	SMEs from appropriate mission area provide technical knowledge
	Industry		

Figure 5-2. "Capability Needs Assessment" Function Roles and Responsibilities

The first step of the CNA working group will be to define several use cases, or environments in which the mission area will be evaluated. This should include a nominal case, for standard daily operations, and any threat-based scenarios that are likely given our analysis of the adversary's future capabilities. As our senior leaders have emphasized, we can no longer assume that space will be a sanctuary, and every mission area must have use cases to evaluate how we want our systems to operate in this future threatened environment.

The second step is to develop activity diagrams to describe nominal and scenario-based operations. The working group should begin with a day-in-the-life evaluation of how various systems or components should operate, and what activities they will perform. Specific actions may be defined as external influences on the system that cause the system to perform another activity.

These activity diagrams are meant to be high-level, just to capture the intent of the future capabilities we believe we need to have. In Step 3, the group will write a definition for the functional capability we wish the system to have to perform that activity, using a solution neutral statement. For example, an SSA sensor may detect an adversarily capability moving towards one of our sensitive space capabilities. In this case, the "SSA Sensor" is the object, and the action would be "Detect threat." We might have two desired responses, one for DCS and one for OCS. The DCS activity could then be defined as "Defend US Asset." In Step 3, we might further define this activity to be one or more functional capabilities we think will be necessary. One might be "Internal defense against threat." Another might be "External defense against threat." This would capture two distinct capabilities we need to develop for the future-the first being an on-board defense capability against threats, and the second being a defensive capability not related to the asset itself. These solution neutral statements allow for consideration of many different types of threats, and many potential solutions.

The other crucial part of Step 3 is to define the interfaces between the objects, actions, and activities required to achieve these functions. Again, this can be very high level to begin, but we need to begin to capture the dependencies between our systems, how we become aware of external actions, and how we control and inform our activities. We will discover additional relationships that must be defined in later steps, but this step will begin to force the working group to consider how the complex architecture must be structured and connected in order to achieve the desired functions.

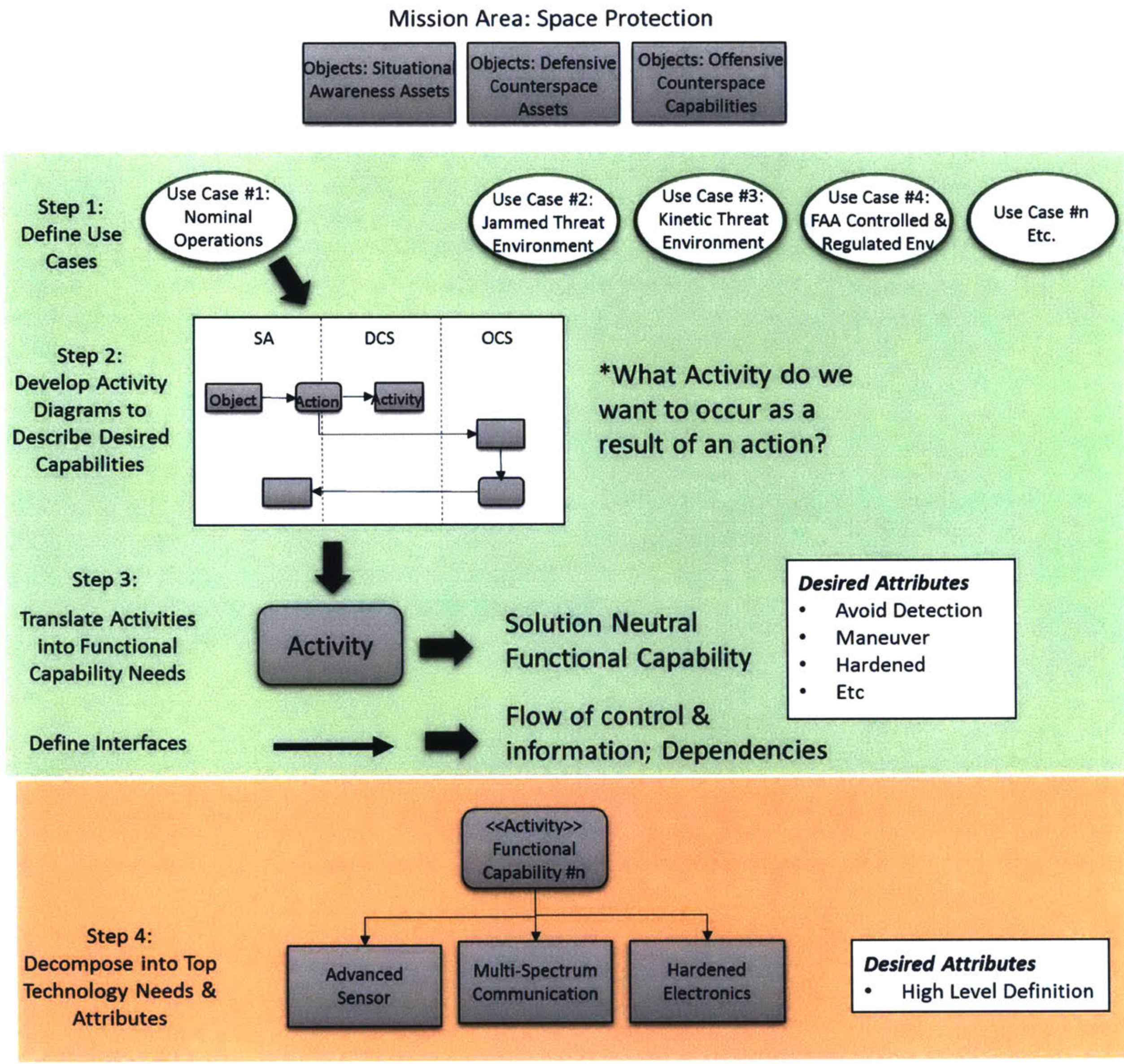


Figure 5-3. Capability Needs Assessment Process

Step 4 begins considering specific technological capabilities that could potentially provide the desired functions. It should also identify any key technological needs that are required to advance the current capabilities. For example, specific sensor technology, communication needs, power requirements, these are all areas that we know are critical to advancing our current capabilities, and should be captured as technology needs. We should also capture any technology needs that do not exist today, but if they are advanced sufficiently, they could contribute to the desired function. For example, optical communications is a promising new technology that may allow for vast improvements in data transfer rates. There are several critical technology components, besides the laser itself, upon which this technology is dependent, such as very precise attitude determination and control. Each of these technology needs should be captured as a separate object in the model, including the desired attributes of each. All of the technology needs that are identified for this mission area will go into a library, which any other mission area can consider and access for applicability to their functions as well.

By building this library of technical needs, including their relationships to each mission area functional capability, we can align technology development early on with its potential mission area users, and also identify synergies and multi-use opportunities.

Step 5, the final step for this working group, is to map the relationships of each functional capability with all other functional capabilities identified, then to do the same for all technology needs. Using the DSM approach described in Section 4.3, we can build a matrix of the relationships to fully identify all of the relationships across mission areas. Figure 5-4 shows an example of the important dependency we may choose to capture between functional capabilities in different mission areas. The turquoise box shows where a function must coordinate with another function to operate. In this example, we could imagine that Functional Capability #1 is a command and control function that interfaces with many other functional capabilities.

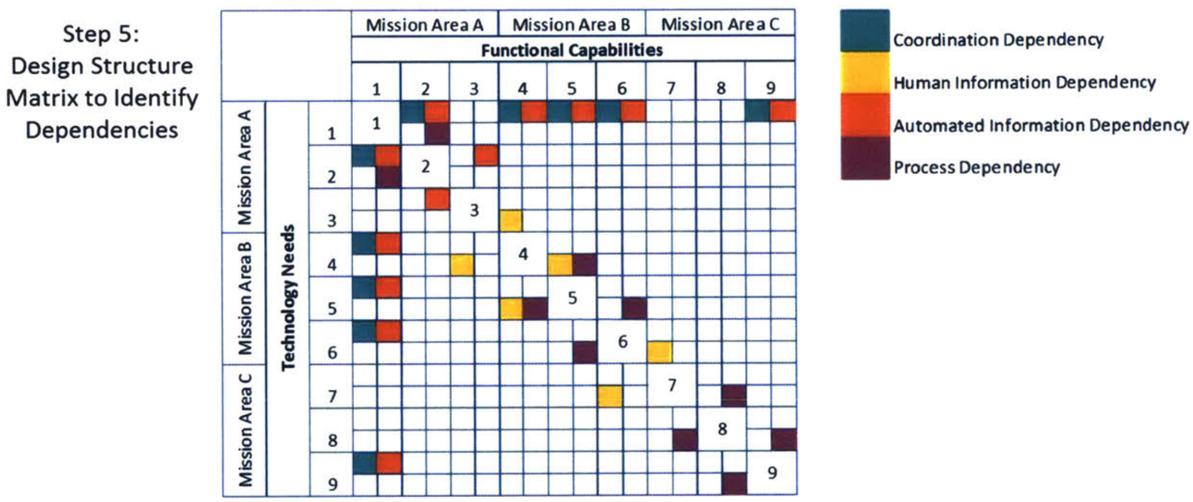


Figure 5-4. Example Functional Capabilities DSM

The yellow and red boxes are important to capture where functional capabilities must share information, and whether that information requires a human-in-the-loop, or if it is an automated data transfer. Although we are increasingly moving toward automated operations, there are some functional capabilities that may be too sensitive to rely on machine analysis, and we may require human decision making before that information is provided to another system. Finally, the purple boxes represent a process dependency, where two or more functions are related in a process. For highly complex processes, a DSM is often completed to analyze process alone. In this case, however, it is not necessary at the high level.

Figure 5-5 shows a DSM for the specific technology needs identified by the working group. The four types of relationships identified here are complementary (green), dependent (blue), highly dependent (red), and "either/or" (purple). The specific categories may be modified by the working group if they find other more applicable categories, but the example here was to show the value of identifying various types of relationships. Complementary relationships may identify synergies or capabilities that are amplified by partner projects. Dependent technologies may rely on another technology that already exists, whereas highly dependent technologies may rely on other technologies advancing to a greater capability before it can operate. Relationships captured as "either/or" signifies that an alternative technology may serve the same function but with a different approach. In these cases, multiple mission areas may have a need for a technology to support a function, but the mission area working groups have identified different technology needs to achieve them. When completing the DSM, the teams may identify that either approach could benefit either mission area.

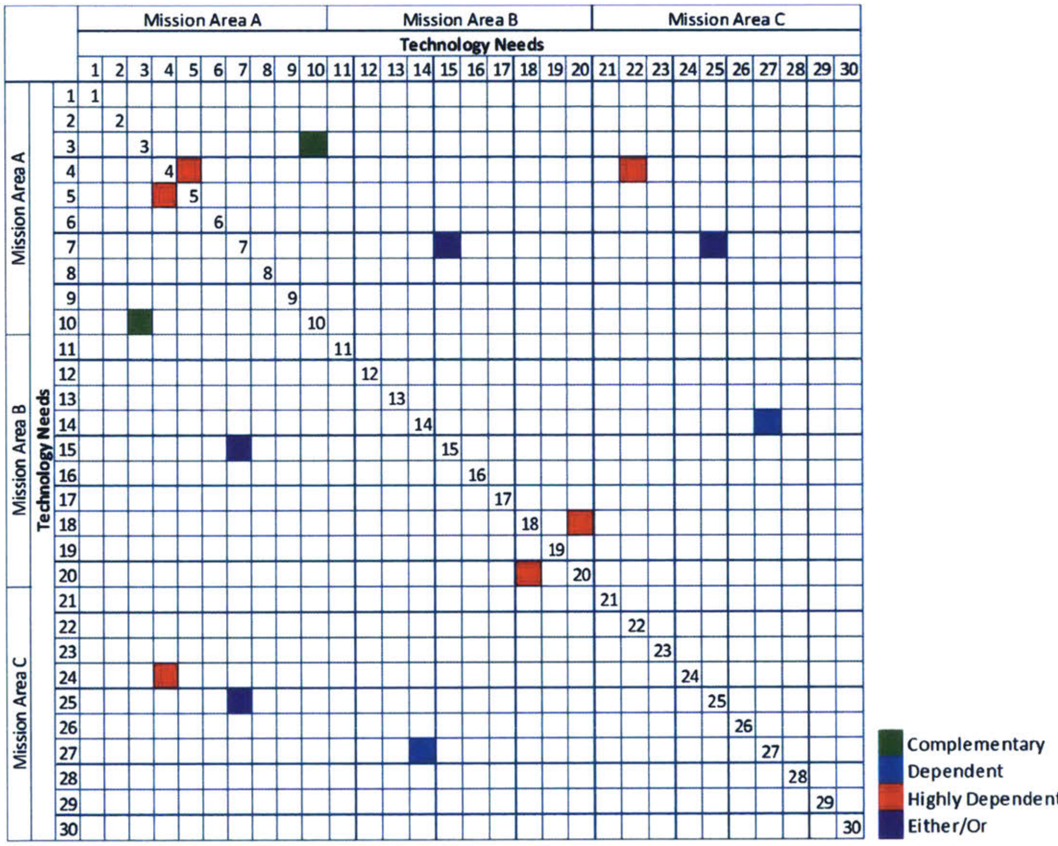


Figure 5-5. Example Technology Needs DSM

These are just examples of how the DSMs could be categorized, but the AFSPC Chief Architect could use the DSM principle to achieve many different angles of analysis. In the MBSE model, the dependencies identified above can now be added to the data captured for each functional capability as attributes and interfaces. This expands our understanding of critical relationships, and allows us to trace our needs across multiple mission areas.

Once these activities are repeated for multiple mission areas, we will end with an integrated model of the future technology needs and their dependencies. Figure 5-6 shows how the cross-mission area technology needs might support multiple functional capabilities in multiple mission areas. Other technology needs, such as specific sensors, may directly support only one mission area. The third layer shown here, is how various 6.1 and 6.2 efforts might apply to different technology needs. While the 6.1 capabilities will not be captured in the model, the R&D entities conducting this type of research will have access to the model and technology priorities for consideration in shaping their 6.1 efforts.

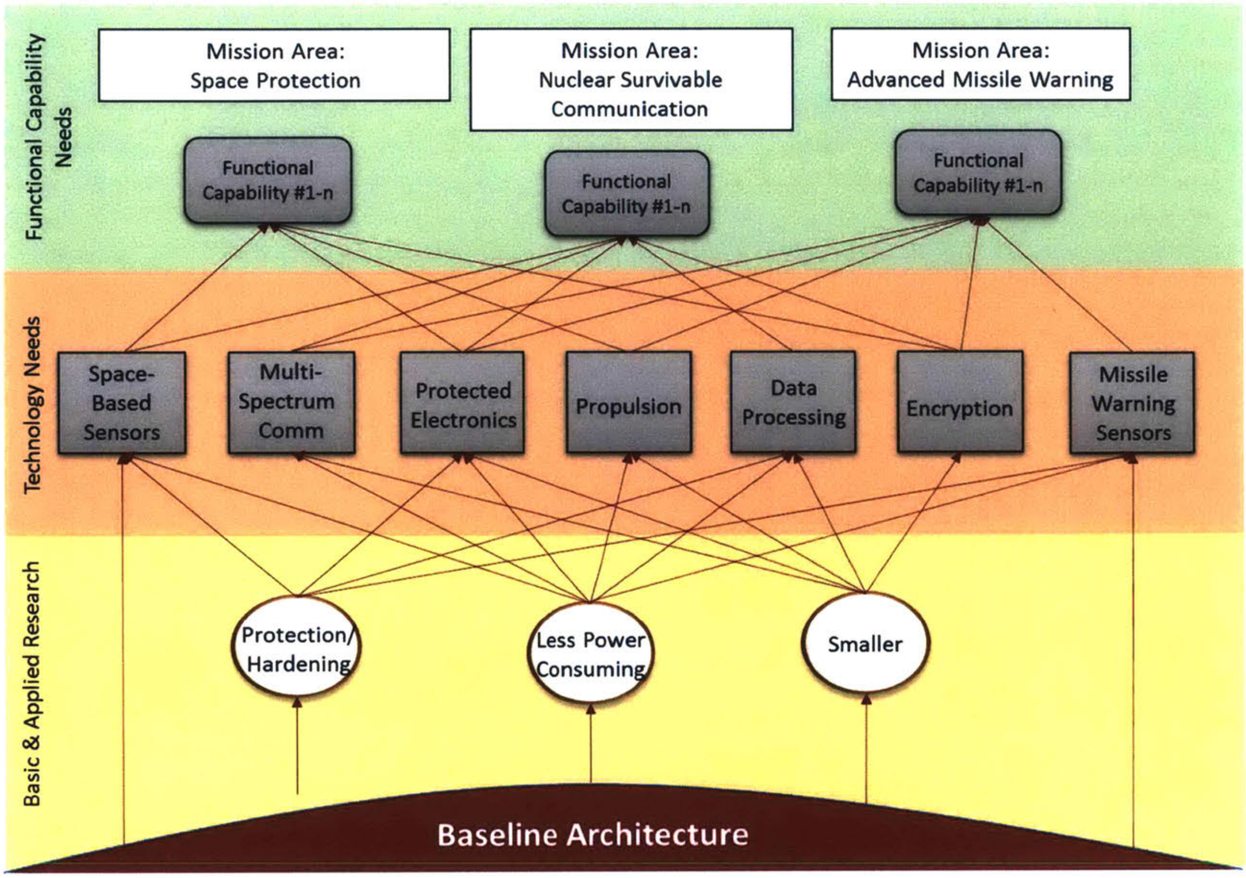


Figure 5-6. Example Integrated Model

5.1.2 Technology Roadmapping

5.1.2.1 Roadmap Working Group

The next function in the PAP is to lay these technology needs against a schedule in an integrated roadmap. The Roadmap Working Group (RWG) should be chaired by the PDSA, due to the number of DoD-level processes and decisions that could be tied to this product. The AFSPC/CA would be designated the Executive Agent for the execution and facilitation of the roadmap and Roadmap Working Group. Currently, the Space COI, AFSPC, and SMC are charged with or attempting to do some form of roadmapping, but this Roadmap Working Group would combine those endeavors with all stakeholders participation into one integrated effort. Stakeholders such as SAF/AQS and the SPOs would be critical to collaborating in this process, to ensure the future planning happening across the Department is all captured and consistent.

With the right participation and buy-in from the stakeholders, the roadmap can be developed in MBSE and serve as a baseline plan supporting the DAS and PPBE processes. The focus will be on developing a roadmap for each mission area, but due to the previous dependencies already identified, time-constraints and time-dependencies that cross mission area boundaries can be easily identified.

	Stakeholders	Technology Roadmapping	R&R Definition
Acquisition	**PDSA Staff**	*Chair*	Makes final recommendations to DepSecDef; DoD level advocate for use of Roadmap
Acquisition	**JCIDS FCBs**	*Support*	Represents CCMD capability needs; Advocate JCIDS support for Roadmap plans
Acquisition	**PPBE** (HQ staffs; CAPE)	*Support*	Ensures Roadmap is linked with PPBE plans; Advocates PPBE for budget justifications
Acquisition	**DAS** (SAF/AQ; OSD/AT&L)	*Support*	Supports with info about planned acquisition timelines and constraints
Pre-Acquisition	**ASD(R&E)** (ExCom/COI)		
Pre-Acquisition	**USSTRATCOM** (JFCC Space)		
Pre-Acquisition	**AFSPC** (A5/Chief Architect)	*EA*	Executive Agent- Owns and facilitates this function
Pre-Acquisition	**SMC, ONR** (SMC/AD)	*Support*	Provides integration support for entire process across all mission areas
Pre-Acquisition	**SPOs** (Varies)	*Support*	Provides data- planned acquisition timelines, on-ramp opps, tech timeline feasibility
Pre-Acquisition	**R&D Entities** (Labs, FFRDC, DARPA, etc)	*Support*	Provides feasibility assessment for tech insertion objectives
Pre-Acquisition	**Industry**		

Table 5-3. "Technology Roadmapping" Function Roles and Responsibilities

5.1.2.2 Roadmap Development

By developing a mission area roadmap with all of the stakeholders participation, we can better align the R&D efforts that will flow into the future acquisitions through three technology insertion opportunities. An example roadmap with these opportunities is shown in Figure 5-7.

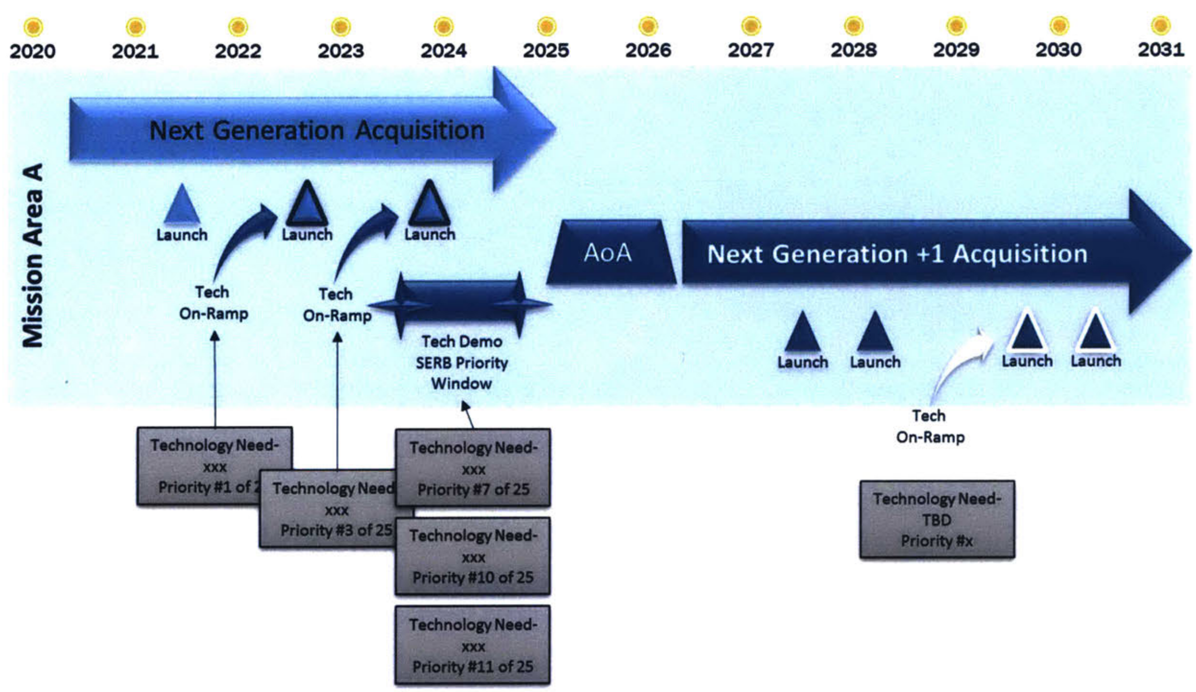


Figure 5-7. Example Mission Area Roadmap

Technology On-ramp opportunities: To align with this roadmap, each system program office (SPO) will need to identify all on-ramp opportunities to add or demonstrate technology on the existing or in-work acquisition satellites. All size, weight, and power constraints allocated to these opportunities can be captured in the model, as well as any interface requirements. If the SPO has already identified specific mission capabilities or priorities for these on-ramp opportunities, they should be captured as technology needs that align with the future functional capabilities for that mission area, and those priorities can then be linked in the model to those on-ramp opportunities.

Several of the major mission areas currently receive funding for the Space Modernization Initiative (SMI), which Congress intends be used "to make evolutionary upgrades to existing programs to enhance mission effectiveness and avoid parts obsolescence." [135] The use of SMI funds has become contentious with Congress, and in the FY 2016 Congressional Marks, the House Appropriations Committee cut $191 million from the Advanced Extremely High Frequency (AEHF) and SBIRS programs, citing, "The Government Accountability Office has found that these efforts are limited by lack of direction, are focused on isolated technologies, and are not set up to identify insertion points for a desired future system." [135]

The use of this roadmap will allow the DoD to clearly show the linkage between the intended use of the SMI funds, and the future functional capabilities and specific insertion points identified for these technologies.

Technology demonstrations prior to AoA: In addition to on-ramp opportunities, a specific priority window for technology demonstration, 1-2 years prior to the next planned AoA for each mission area, should be allocated to allow all R&D entities developing technology needs an opportunity to compete for a launch. The competitive selection process for this technology demonstration opportunity would be managed by the SERB, and will be discussed in greater detail below, as part of the Technology Demonstration Function.

AoA for next generation PoR: Participants in the RWG will include representatives from OSD/AT&L and SAF/AQS, to ensure the future acquisition plans for developing the next Program of Record (PoR) are captured accurately. The anticipated AoA timeframes will be included on the roadmap, to clearly articulate the final opportunity that R&D entities will have to present their technology advancements for consideration in the next generation system.

Technologies that are not yet advanced enough to compete for an on-orbit demonstration, or that have been developed outside of the DoD entities can still compete for consideration at the AoA milestone. There will be a specific submission date prior to the AoA analysis when all products will be due.

Alignment of Technology Objectives with Schedule: Once the timeline for the roadmap is established, the RWG must set target implementation plans for the technology needs and functional capabilities. Some of these may align with on-ramp opportunities for early demonstration or upgrades to operational capabilities. Others may be targeted for inclusion in the next PoR. Using SME and SPO input regarding realistic timeframes, every technology need and functional capability must have a target date. The RWG must keep in mind that these are objective capabilities, not firm DoD requirements, and they have not yet been validated by the JCIDS process. These may be "stretch goals" that we are unable to reach in the objective time frames, and the firm requirements will still come from the JCIDS process prior to the AoA. These objectives are intended to draw a clearer path toward the future for each functional capability, and create a deliberate pipeline for the development of the technologies necessary to achieve those capabilities.

This approach for technology roadmapping is consistent with the GAO's recommendation, specifically for the SBIRS future planning, to "establish a technology insertion plan that identifies specific needs, technologies, and insertion points, to ensure planning efforts are clearly aligned with the follow-on system and that past problems are not repeated." [14]

5.1.2.3 Core Function Master Plan & Roadmap Integration

AFSPC, as the CFLI, will be responsible for analyzing the mission area roadmaps for constraints, conflicts, and integration across the mission area boundaries. The AFSPC/CA will present this analysis to the RWG, along with recommendations for any changes that may be necessary in a specific mission area. Additionally, the AFSPC/CA will look for opportunities to partner, and for synergies that may meet the timelines for multiple mission areas. Particularly, the AFSPC/CA will examine the technology needs that have been identified that cross multiple mission areas, and the need dates for each mission area.

Again, it should be reiterated that the entire roadmap function can be documented using the MBSE approach, and the elements of the model developed in the CNA can be directly linked to the roadmap milestones discussed above. A specific roadmap viewpoint would give access to stakeholders to view the roadmap in a simplified or abstracted format, and would allow for artifacts to be generated for use in other products.

Thus, the roadmap product can be used to create the CFMP, with other viewpoints of the integrated model as necessary to communicate the master plan. Ideally, the CFMP would simply reference the model and its integrated roadmap, and direct stakeholders to access the model (or a releasable portion of the model made openly available).

5.1.3 Prioritization

Within each mission area, the CNA working group will prioritize the list of technology needs and the list of functional capabilities. At the enterprise level, the AFSPC/CA will analyze the prioritization recommendations from each mission area, and integrate them into a master priority list. This master list will also take into account cross-mission area dependencies that may make some technology needs or functional capabilities a higher priority based on their relationship with other mission areas.

The master priority list will then be presented to the PDSA for acceptance or modification. PDSA is the final approval authority as the integrator across the DoD. The master priority list will then be documented in the model, and each technology need and functional capability will be linked to this list, so if it is updated or changed, this information is automatically propagated across the model.

	Stakeholders	Prioritization	*R&R Definition*
Acquisition	**PDSA Staff**	*Approval*	Receives recommendations from AFSPC/CA; Makes final recommendations to DepSecDef
Acquisition	**JCIDS FCBs**		Inputs captured during CNA process
Acquisition	**PPBE** (HQ staffs; CAPE)		
Acquisition	**DAS** (SAF/AQ; OSD/AT&L)		
Pre-Acquisition	**ASD(R&E)** (ExCom/COI)		Inputs captured during CNA process
Pre-Acquisition	**USSTRATCOM** (JFCC Space)		Inputs captured during CNA process
Pre-Acquisition	**AFSPC** (A5/Chief Architect)	*EA*	Executive Agent- Owns and facilitates this function
Pre-Acquisition	**SMC, ONR** (SMC/AD)	*Support*	Provides support to AFSPC/CA as necessary
Pre-Acquisition	**SPOs** (Varies)		Inputs captured during CNA process
Pre-Acquisition	**R&D Entities** (Labs, FFRDC, DARPA, etc)		Inputs captured during CNA process
Pre-Acquisition	**Industry**		

Table 5-4. "Prioritization" Function Roles and Responsibilities

5.1.4 Communicate Priorities & Roadmap

The most important function necessary to aligning the industry is to communicate the priorities clearly, in a way that R&D entities can use for their own decision making. It is critical that the PDSA own this role, and ensure the message is being received across the entire DoD. The AFSPC/CA, as the Executive Agent for the model and roadmap functions, will facilitate the access to the information.

With this MBSE approach, the priorities and viewpoints of the model and roadmap can be made available through a web portal for users to access. Their rights may be restricted to view only, and may be restricted to only certain viewpoints with access to drill into the decomposition of select data. The more broadly this access can be shared with the R&D community, the better they can make decisions about their investments, and better align the timing of their work with the integrated roadmap.

	Stakeholders	Communicate Priorities & Roadmap	R&R Definition
Acquisition	**PDSA Staff**	**Chair**	Pushes priorities out to entire DoD Space Enterprise
Acquisition	**JCIDS FCBs**	*Receive Info*	Receives & shares with CCMDs
Acquisition	**PPBE** (HQ staffs; CAPE)	*Receive Info*	Uses for funding decision making
Acquisition	**DAS** (SAF/AQ; OSD/AT&L)	*Receive Info*	Uses for acquisition decisions and planning
Pre-Acquisition	**ASD(R&E)** (ExCom/COI)	*Receive Info*	Integrates with other DoD R&D efforts
Pre-Acquisition	**USSTRATCOM** (JFCC Space)	*Receive Info*	Use for future operational planning
Pre-Acquisition	**AFSPC** (A5/Chief Architect)	**EA**	Executive Agent- Owns and facilitates this function
Pre-Acquisition	**SMC, ONR** (SMC/AD)	*Receive Info*	Uses for decision making
Pre-Acquisition	**SPOs** (Varies)	*Receive Info*	Uses for decision making
Pre-Acquisition	**R&D Entities** (Labs, FFRDC, DARPA, etc)	*Receive Info*	Uses to align R&D efforts with tech insertion opportunities
Pre-Acquisition	**Industry**	*Receive Info*	Uses to align R&D efforts with tech insertion opportunities

Table 5-5. "Communicate" Function Roles and Responsibilities

5.1.4.1 Classification

The challenge with this, of course, is security and the classification of this data. Figure 5-8 summarizes how the model layers should be maintained at different classification levels. One of the benefits to using a modular system like a SysML MBSE approach, is that the model can be segregated so that portions containing classified data can be removed, and the remaining portions can be extracted and maintained at a lower classification level. As this lower level data is updated, it can be re-ingested or updated at the higher levels when necessary. Additionally, through the use of abstraction and Object ID numbers in the model, references can be established so that, at a lower level, you may see a linkage to another Object ID and the relevant mission area, but will not see the object name or any details if it is classified at a higher level.

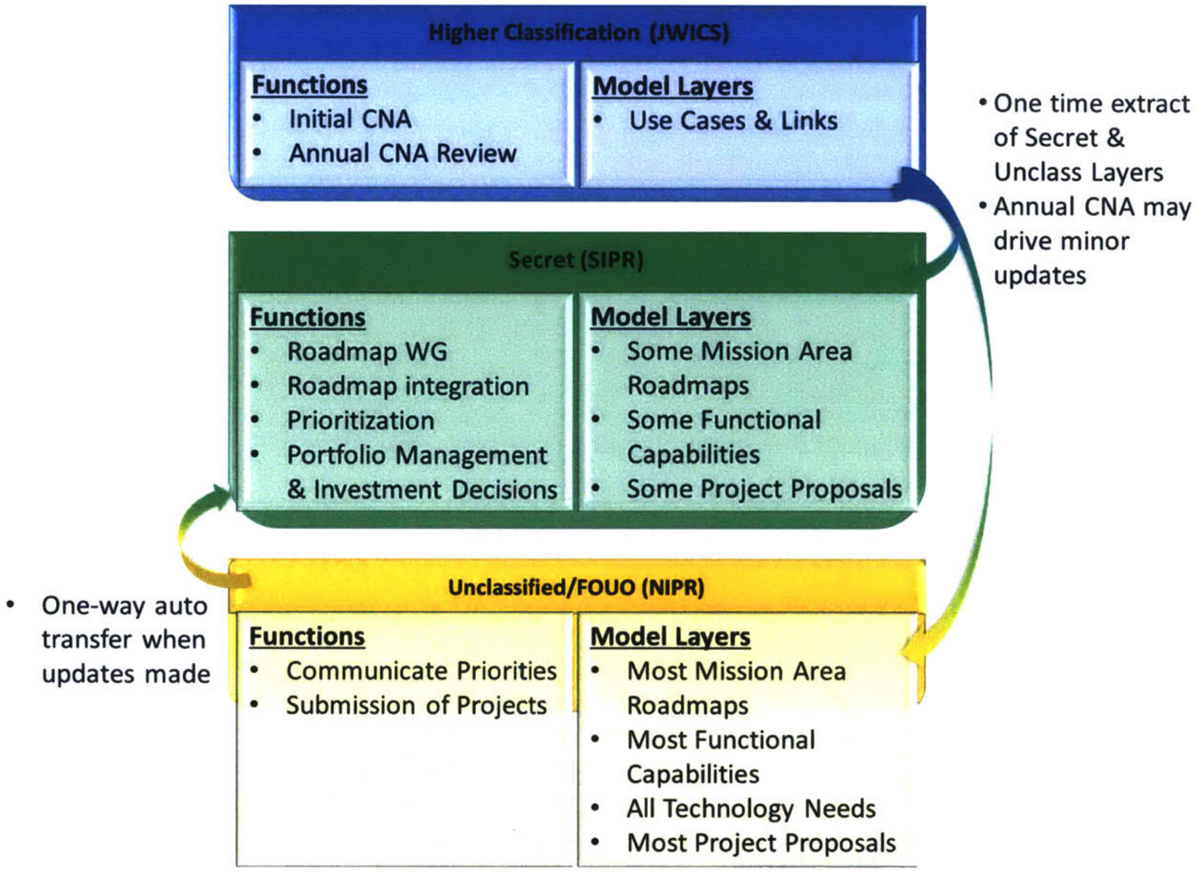


Figure 5-8. Function & Layer Classification of the Model

The most sensitive part of this model and the data it contains is the specific use cases for each mission area, including the expected threat actions and subsequent desired responses. This clearly would require access to Top Secret and above information, and must be maintained at this level. This data is critical to the CNA process so that lower level technology needs can be decomposed, but is not critical to the stakeholders executing R&D projects. Therefore, there is a portion of this model that must be maintained at a high classification level and will have limited access.

The next most sensitive information would likely be the functional capabilities for certain mission areas, such as protected communications and space protection. The functional capabilities are important to be able to communicate with as broad an audience as possible, although they would still need to be protected at a higher level. The specific classification level would depend on a security review for each mission area, but ideally we will keep all mission area roadmaps and functional capabilities no higher than the Secret level.

The majority of the information in the model is unclassified, and can be maintained on a standard NIPR system. Access to the web portal for the model would require authorization with a unique login, as is done on the Defense Innovation Marketplace for restricted access today. All of the technology needs would be available at the unclassified level, as well as their dependencies on each other, and their dependencies to functional capabilities.

5.1.4.2 Model Use for Communication

By giving the R&D community access to certain viewpoints of the model, we can clearly communicate the technology needs we want them to address, the prioritization of those needs, and the dependencies of those needs on other areas.

Additionally, because these technology needs are directly linked to each mission area roadmap, the timelines for need and potential implementation are completely transparent. In the few mission areas where the mission roadmap itself is classified, we may unmask just the need date for the specific technology without the context of the roadmap. Users who need more information will have to access that portion using the higher classification system, which would have the entire model including the classified data available in the same formats and viewpoints.

5.1.4.3 Uniting the R&D Community

Much of the R&D that is conducted today is not directly tied to a need date or insertion opportunity. Our industry partners spend too much time trying to analyze the timing and opportunities that might benefit their use of IRAD, and our R&D entities are rarely tied directly into a technology maturation plan. Additionally, the SPOs are generally so focused on the current or next generation acquisition that they have little time to communicate with the R&D community consistently. By integrating the technology needs and acquisition plans into this model and roadmap, we can transparently communicate this information so that each organization can align their own investment decisions with our needs.

5.1.5 Portfolio Investment Decisions

5.1.5.1 Basic and Applied Research

Due to the early nature of this research, it is not advantageous to the DoD to try to align 6.1 and 6.2 S&T funding explicitly with the DoD Space Enterprise model and roadmaps. These funds are more appropriately allocated in the method used today, strategic bucketing, where they are spread across all disciplines for general research topics that will advance technologies and concepts without any specificity.

5.1.5.2 Portfolio Management- Near Term

Until a model capability is built that allows for the data-driven analysis of projects, the existing Air Force S&T Group/Board, the Applied Technology Council for Space, and the S&T ExCom should be combined into a Space Portfolio Management Group, chaired by the PDSA, to review the S&T portfolios and investment decisions, and to review, prioritize, and endorse proposals for all space:

- Advanced Technology Demonstrations
- Flagship Capability Concepts
- Joint Capability Technology Demonstrations
- Small Business Innovative Research
- Small Business Technology Transfer
- Rapid Innovation Fund

Each of these existing Boards, Councils, and Committees is already doing this, but in a piecemeal fashion across the DoD Space Enterprise. By combining them into one decision making group that has the authority to commission demonstrations from each of these categories, we can eliminate some duplication of effort and begin to initiate the type of collaboration and cooperation that will be necessary to build a successful MBSE approach.

For the interim, until the prioritized MBSE technology needs are developed, all projects should be clearly aligned with the AFSPC/CC priorities already established. If the major DoD Space Enterprise stakeholders do not feel that the AFSPC/CC space priorities adequately capture the entire DoD Space Enterprise, then the PDSA should envelope these priorities into a temporary Master DoD Space Enterprise priority list, to be used until the full PAP has been implemented under this new recommendation. The first priority for the assessment of all proposed projects should always be its alignment with the existing priorities.

5.1.5.3 Portfolio Management- Intermediate Steps

Once the MBSE approach is up and running in at least one mission area, there should be a focus on transitioning all 6.3 project proposals into an MBSE tool. By the time a project has advanced to the use of Applied Technology Development funding (6.3), it should be aligned with specific technology needs or functional capabilities in the model and roadmap, or whatever enterprise priorities have been established for that mission area.

At this stage, each space enterprise project proposed to an R&D entity, including the labs, FFRDC, DARPA, and government-funded academia and industry projects, would be required to submit the high-level details of their project in a SysML template. The templates should be provided by the AFSPC/CA MBSE team, in a format that could be used with any SysML software-specific tool, so that R&D entities can use whichever MBSE tool they are most comfortable with, or are already using.

On a regular basis, the AFSPC/CA team can ingest the proposed and ongoing projects to analyze how well we are covering each of the technology needs. Initially, this will allow us to review our investments across the space enterprise. From this review, we will likely find areas of overlap and gaps in our investments which we can highlight as areas of concern for the R&D entities to consider in their next round of investment decisions. Figure 5-9 displays conceptually how analyzing projects in this MBSE approach will give us better insight into the R&D projects across the enterprise, and how they might benefit more than one mission area. It also allows us to consider "technology push" alternatives to achieving a functional capability other than what we had anticipated in the CNA.

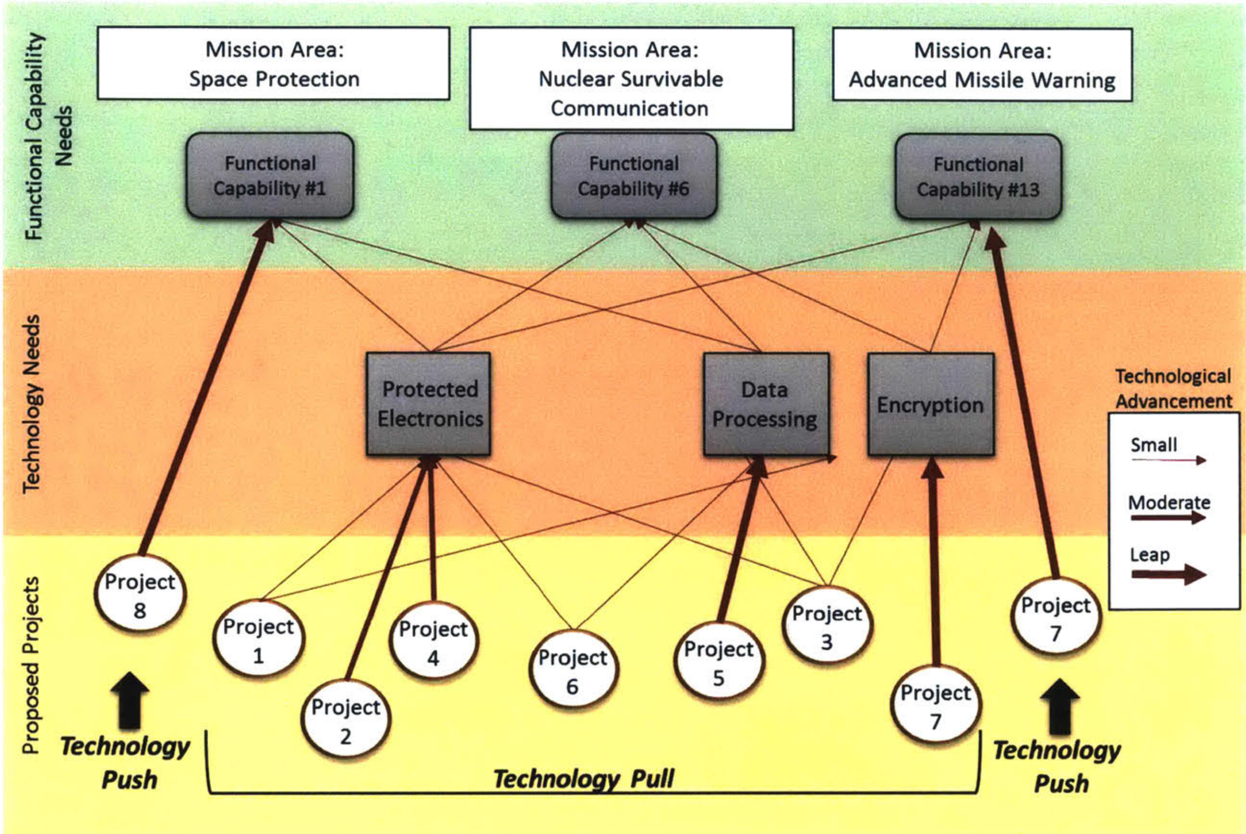


Figure 5-9. Portfolio Management in Model

The existing governance boards and processes for each R&D entity should evolve to use the roadmap as a measure for investment decisions within their own organizations. No project should be considered that doesn't map to a technology need or functional capability unless there is strong justification that this technology may provide an unexpected leap or capability that is not captured in the model today. In this case, that feedback must go back to the CNA during the next annual review for consideration.

5.1.5.4 Portfolio Management- Long Term

As the fidelity of the model and roadmap progresses, and the use of these tools grows, the DoD Space Enterprise will advance to a level of integration where true portfolio management can occur. In order for this to happen, the model must have matured to the point where:

- The dependencies and roadmap details for each mission area have been captured and integrated across mission areas
- All 6.3 funded projects have established MBSE models
- All technology needs (and potentially functional capabilities) have measurable performance objectives against which projects can be analyzed

Once the model is fully functioning in these ways, then an analysis capability can be added to the tool (or can extract the appropriate data from the tool) to conduct multi-objective optimization (MOO). MOO is a capability that has been studied for decades, and applied in many different ways. Fundamentally, it is designed to use computer algorithms to conduct a tradespace analysis factoring in several objectives and constraints. Although the space enterprise is incredibly complex, and would be considering a tremendous number of potential alternatives, the basic data necessary to conduct MOO would already be captured in the model, and defining an MOO approach would be a matter of clearly articulating the stakeholders' constraints and priorities, and developing a tool that could assist the DoD with balancing its R&D investment decisions. This will be discussed in Chapter 6 as an area for future work.

	Stakeholders	Portfolio Investment Decisions	R&R Definition
Acquisition	**PDSA Staff**	**Chair**	
Acquisition	**JCIDS FCBs**	*Support*	Provide CCMD inputs for objectives
Acquisition	**PPBE** (HQ staffs; CAPE)	*Support*	Provides funding constraints
Acquisition	**DAS** (SAF/AQ; OSD/AT&L)	*Support*	Provides acquisition constraints & reviews recommendations
Pre-Acquisition	**ASD(R&E)** (ExCom/COI)	*Support*	Provides SME inputs on assessing projects
Pre-Acquisition	**USSTRATCOM** (JFCC Space)		
Pre-Acquisition	**AFSPC** (A5/Chief Architect)	*EA*	Executive Agent- Owns & facilitates MOO analysis of portfolio, makes recommendations
Pre-Acquisition	**SMC, ONR** (SMC/AD)	*Support*	Provides inputs for objectives & assesses recommendations
Pre-Acquisition	**SPOs** (Varies)	*Support*	Provides inputs for objectives & assesses recommendations
Pre-Acquisition	**R&D Entities** (Labs, FFRDC, DARPA, etc)	*Support*	Provide proposed project models
Pre-Acquisition	**Industry**	*Support*	Provide proposed project models

Table 5-6. "Portfolio Investment Decisions" Function Roles and Responsibilities

Table 5-6 shows what a new Portfolio Management Group (PMG) would look like, chaired by the PDSA, and executed by the AFSPC/CA. Most MOO tools require inputs from all stakeholders to capture the constraints and parameters around the funding decisions. The PMG would participate in that process, and have responsibility for integrating the portfolio decisions in their parent organizations.

5.1.6 Technology Demonstration

One of the most critical stages in R&D development for space systems is to demonstrate the technology in a relevant operating environment. For space systems, this means getting the technology on-orbit. Historically, this has been cost prohibitive, and technology maturation was often limited to a TRL 6, where it was demonstrated in a relevant environment such as a thermal vacuum chamber.

The decreasing size of components and increasing capabilities of space technology is revolutionizing the space industry, particularly in the area of cubesats. With the growth of this new niche in the industry, there is a corresponding growth in opportunity for launching small satellites. Traditional launch providers, such as the United Launch Alliance, are expanding the opportunities for launch cubesats and secondary payloads on their commercial and government launches. There is also an uptick in the number of new launch providers attempting to enter the market for small payloads. In a recent survey of the small launch vehicle industry, Orbital ATK found 22 organizations or vehicles providing or in development to launch payloads smaller than 1000 kg, with at least eight more companies in the works.

Organization	Vehicle Name	Country of Origin	First Launch Date
Boeing	ALASA	USA	Q1 2016
Lockheed Martin	Athena Ic	USA	After contract award
zero2infinity	Bloostar	Spain	
CubeCab	CubeCab	USA	July 2017
Scorpius Space Launch Company	Demi-Sprite	USA	
Rocket Lab	Electron	USA/New Zealand	2015
Firefly	Firefly α	USA	2017
Generation Orbit	GO Launcher 2	USA	Q4 2016
ARCA Space Corporation	Haas 2C	Romania/USA	
Virgin Galactic	LauncherOne	USA	Q4 2016
XCOR Aerospace	Lynx Mark III	USA	2017+
MISHAAL Aerospace	M-OV	USA	
Orbital ATK	Minotaur I	USA	2000
Garvey Spacecraft Corporation	Nanosat Launch Vehicle	USA	
Interorbital Systems	NEPTUNE N5	USA	Q4 2015
Open Space Orbital	Neutrino I	Canada	
Orbital ATK	Pegasus	USA	1990
Celestia Aerospace	Sagitarius Space Arrow	Spain	Q1 2016
Ventions	SALVO	USA	2015
Swiss Space Systems	SOAR	Switzerland	2017
U. Hawaii, Aerojet Rocketdyne, Sandia	Super Strypi	USA	October 2015
Lin Industrial	Таймыр	Russia	

Table 5-7. Survey of Small Launch Vehicle Providers (Source: Orbital ATK [136]*)*

Increasing the number of technologies we demonstrate on orbit will not help the acquisition process, however, unless it's well aligned with the potential future architecture, and interdependencies with other advancements in technology are well understood. A lesson learned from DARPA's system F6 project was that advancing a technology without a specific implementation plan resulted in a limited effective solution for an operational system. [96] Although new technology innovation is important, it is just as critical that we understand how it might interface with ground and user segments, operational impacts, and the timing of when it is needed to support the next generation AoA on technology on-ramp decisions. This is why the ongoing discussions about disaggregating future satellite constellations have become so challenging, because although the technology for a sensor or capability may be small enough and capable enough to put onto a smaller satellite than historically used, we are struggling to capture the impacts to the overall system architecture if we make a sweeping change to the space segment. [96]

For these reasons, it is important that we manage the technology demonstration opportunities in a well-organized way, to ensure alignment with the mission area roadmaps.

5.1.6.1 Modify the SERB Process

Managing the technology demonstration process is a function that exists today, primarily with the SERB and STP, as described in Section 3.6. There are several ways we can improve this process today, to begin the alignment of technology maturation against enterprise priorities.

Table 5-8 shows that, like the previous functions, the SERB would be executed by the AFSPC/CA, and chaired by the PDSA. This is a change from the SERB today, which has SAF/AQS as the EA and the PDSA as the Primary Advisor. This change to AFSPC/CA as the EA would better align the SERB with the rest of the PAP functions in this recommendation, and maintains the same collaborative approach.

5.1.6.1.1 Intermediate Steps

All Experiments Reviewed by SERB: First, all space experiments across the DoD, regardless of whether they have program funding or desire a centrally-funded launch from the SERB/STP process, should be required to present their project to the SERB. For experiments with dedicated launch funding, or funded from other sources, the SERB will provide feedback to the parent organization about this project versus the others in consideration. For projects that the SERB designates "supported," it will include these in all summary documentation as supported experiments, and will provide advocacy in the PPBE process. For experiments that are deemed "unsupported," feedback will be provided to the parent organization about why this project is not compelling enough or inferior to others that are meeting the board, and will make recommendations about how the launch funding for that project might be reallocated to other experiments within that parent organization.

	Stakeholders	Technology Demo	R&R Definition
Acquisition	PDSA Staff	Chair	Chairs the SERB and reviews STP execution
Acquisition	JCIDS FCBs		
Acquisition	PPBE (HQ staffs; CAPE)		
Acquisition	DAS (SAF/AQ; OSD/AT&L)	Support	
Pre-Acquisition	ASD(R&E) (ExCom/COI)	Support	Provides SME expertise for project assessment
Pre-Acquisition	USSTRATCOM (JFCC Space)		
Pre-Acquisition	AFSPC (A5/Chief Architect)	EA	Should own the SERB process
Pre-Acquisition	SMC, ONR (SMC/AD)	Support	Provides SME expertise for project assessment & deconfliction with SMI
Pre-Acquisition	SPOs (Varies)	Support	Provides SME expertise for project assessment
Pre-Acquisition	R&D Entities (Labs, FFRDC, DARPA, etc)	Submit	Provide proposed project models
Pre-Acquisition	Industry	Submit	Provide proposed project models

Table 5-8. "Technology Demonstration" Function Roles and Responsibilities

SERB Scoring Criteria: Next, the scoring for the SERB process must be reexamined to consider the AFSPC/CC-directed priorities that have been communicated to the space enterprise. In absence of an integrated model and roadmap, for now, the SERB scoring should be aligned with Gen Hyten's priorities, or the driving priorities that have been given to that parent organization (such as the other Services). Ideally, the PDSA should integrate all of the existing priorities into one clear DoD Space Enterprise list of priorities, with inputs from the stakeholders, but ultimately recommended to the SECDEF as the integrated priority list. In addition to whichever priority list is available, the SERB should be taking into consideration how many mission areas the technology will support, and how much the proposed experiment is able to advance that particular technology.

These processes are intermediate steps toward aligning projects against the enterprise priorities, but will begin to shift the thinking that all demonstration decisions will be based on enterprise priorities and centrally supported or funded.

5.1.6.1.2 Long-Term Steps

Ultimately, a model submission from each project will be used as a means for evaluating how well the project aligns with the integrated roadmap. Since all 6.3 projects will have previously been required to submit their projects in this model format, this will only require assurance that the model being considered is current, and specific intent to compete for either a SPO-provided on-ramp or STP provided launch opportunity.

Funding: The STP budget should be a high priority for the PDSA to support in the PPBE process, to both increase the number of launch opportunities, and incentivize compliance with eventual policy that all experiment launch funding must come from either the SMI line in the SPO for on-ramp opportunities, or from the SERB prioritization process.

SERB Prioritization: In addition to the current membership, the SPOs would be invited to participate to provide feedback on the specific technology being developed for their mission areas. Each year, all available launch opportunities would be examined, and a set priority scheme that aligns with the upcoming AoAs would be established. Proposed projects that meet specific technology needs or functional capabilities for upcoming AoA consideration will be given a priority window in which they must be considered first. The SERB scoring will then look at projects with the following priorities considered:

1) Mission Area Priority Window Prior to AoA
2) Project addresses needs in multiple mission areas
3) Project addresses multiple technology needs or functional capabilities
4) Magnitude of technology advancement
5) Timing alignment with integrated roadmap

Experiments must be considered for their applicability to both the technology needs and functional capabilities identified for two reasons. First, if there are multiple projects in consideration for the same technology need, then they can be weighed against each other, and their broader application to other mission areas can be reviewed. This directly supports the "Technology Pull" aspect of the MBSE approach developed in the CNA working groups. We must also consider "Technology Push" from any source, which is why all projects will also be considered against the functional capabilities level of needs identified in the CNA. Any R&D entity, including industry-funded IRAD, that develops a novel new approach to achieving a functional capability that bypasses or leaps over the expected technology needs can be given equal consideration against all other projects in the pipeline for that capability.

Special consideration would have to be given on the rare occasion that a project is proposed that does not align with any of the identified functional capabilities, or creates a new, unexpected capability. These projects should be considered by the appropriate CNA working groups for addition to the MBSE model so that they can be incorporated in the roadmaps, and to ensure we do not unintentionally develop duplicative capabilities.

5.1.6.2 Increase Launch Opportunities

Today, the DoD is not highly involved in the evolution of the small launch vehicle industry. One area for future research, is whether the government should be tracking these advances more deliberately, and whether funding or partnerships might benefit the R&D community. Perhaps a tiered approach to the SERB scoring could be considered, where projects that are less likely to receive a funded launch through STP, but still have promising technology capabilities, are tiered for test or more risky launch opportunities. If the choice is between no launch and a risky but inexpensive launch, which also advances the small launch vehicle industry base, the risk may be worth the chance.

5.1.7 Transition

The outcome of this entire PAP is a wealth of technology that is well understood and deliberately matured for future acquisition consideration. The more we can achieve in the pre-acquisition process, the better we will be setting our future programs of record up for success.

Not only will the future programs have a sufficient breadth of technology to analyze for their programs, but they will have an understanding of the future functional capabilities toward which the Department is heading. They will also have a model that captures these needs and the initial stages of a project model, with some of the high level capabilities already defined.

	Stakeholders	Transition	R&R Definition
Acquisition	**PDSA Staff**	*Oversight*	Oversees and reviews tech transfer status
Acquisition	**JCIDS FCBs**	*Support*	Conduct AoAs, make recommendations on PoR
Acquisition	**PPBE** (HQ staffs; CAPE)	*Support*	POM for new PoR
Acquisition	**DAS** (SAF/AQ; OSD/AT&L)	*EA*	Executive Agent- Responsible for technology transfer from R&D into DAS program of record
Pre-Acquisition	**ASD(R&E)** (ExCom/COI)		
Pre-Acquisition	**USSTRATCOM** (JFCC Space)		
Pre-Acquisition	**AFSPC** (A5/Chief Architect)	*Support*	Supports model transition to Acq organization
Pre-Acquisition	**SMC, ONR** (SMC/AD)		
Pre-Acquisition	**SPOs** (Varies)	*Support*	Receives & develops new PoR
Pre-Acquisition	**R&D Entities** (Labs, FFRDC, DARPA, etc)	*Support*	Transitions tech out of R&D organization
Pre-Acquisition	**Industry**	*Support*	Transitions tech out of R&D organization

Table 5-9. "Transition" Function Roles and Responsibilities

After close participation in this process, Office of the Assistant Secretary for Acquisition, Space Programs (SAF/AQS) should have responsibility for facilitating and executing the technology transfer from the R&D entity to the program office and industry partner doing the development. This will be supported by AFSPC/CA, who will transition the relevant model information to the industry partner.

As the R&D community transitions to the MBSE approach to comply with this process, they will also become well versed in using MBSE tools. As they enter the technology transition phase, where they pass designs to industry partners for development and integration, model-based documentation will improve the transition process.

5.2 Streamlined Governance Structure

As discussed in Chapter 3, there are a number of different levels and methods of governance that disperse the decision making for space R&D throughout the community. Following the first tenet air power, we need to establish a collaborative approach to centralize decision making processes, and allow the R&D entities to focus on executing their projects with clear alignment to future space enterprise needs. This requires disbanding existing oversight entities that only represent a portion of the space enterprise, but allowing the key stakeholders to have a voice and participate throughout the new process.

The other shift we need to make for the DoD Space Enterprise is to adjust the oversight of space S&T decisions from ASD(R&E), to the authority of the PDSA. It is critical that we look to the future of space holistically, rather than looking at it from the S&T lens. We need to focus on capturing specific technology maturation plans from S&T through future programs of record for the space enterprise and its mission areas. Under the ASD(R&E) umbrella, the roadmapping function is not specifically aligned with future space functional capabilities as envisioned by the broader space community.

To oversee this aspect of the space enterprise, we would rely on the Defense Space Council, chaired by the PDSA, which is an existing governance entity that already has participation from all critical stakeholders across the DoD Space Enterprise. A special session of the DSC, which we would call "DSC Prime," would be convened to include the additional R&D stakeholders, such as OSD(R&E), AFRL and NRL, with invitations extended to senior leaders from FFRDC. In the DSC Prime, the Executive Agent for each function in the PAP would present the status or results of their work to the DSC Prime for situational awareness, prior to the PDSA presenting the results to the DepSecDef. This provides the DSC members insight into how the future is being shaped by the PAP process, and allows the DSC to see the final products being developed collaboratively by members of their organization.

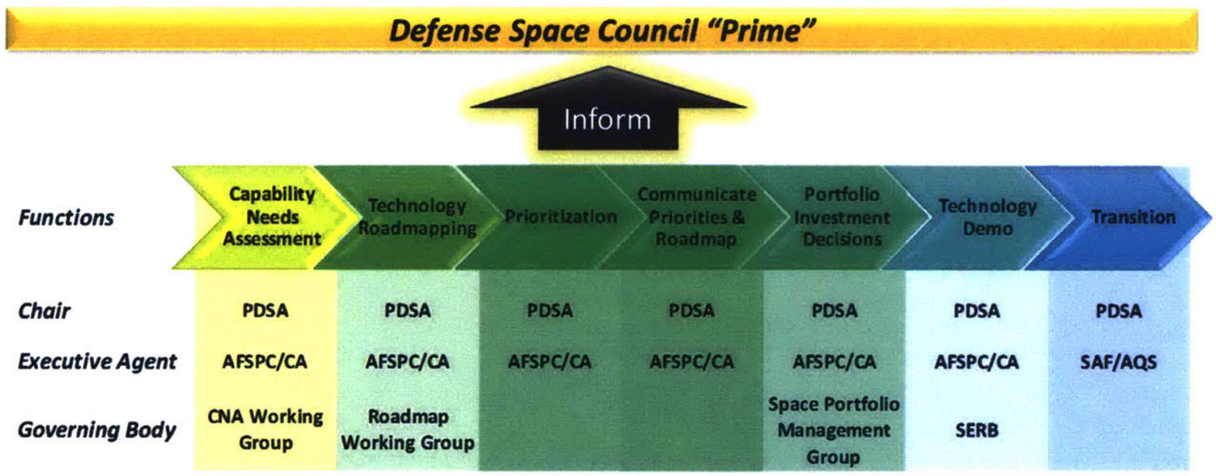


Figure 5-10. Pre-Acquisition Process Governance for the DoD Space Enterprise

Figure 5-10 summarizes the governance entities as described throughout Chapter 5, and shows that regular feedback from this process would inform the DSC Prime. The phased implementation of this transition is discussed in the next section, although the timeline for implementation is left for future work.

5.3 Transition to Recommended Solution

Many of the ideas in this recommendation are not new, but have been recognized as necessary for many years. Some of the proposed changes discussed in Phase 1 are already in discussion to some degree, as the DoD Space Enterprise is trying to shift its focus to Gen Hyten's Space Enterprise Vision.

5.3.1 Phase 1: What We Can Do Now

Although it will take time to develop the full integrated priority list for future space capabilities, we do have Gen Hyten's priorities already established and being communicated throughout the community. The PDSA, representing the entire DoD, should either endorse this list, or modify it to integrate with the other Service and organization priorities that exist today, to create an interim DoD Space Enterprise priority list, as a placeholder until the recommended PAP has generated a fully integrated future priorities list. Regardless of which list the PDSA choses to endorse, we need to begin to transition the thought process and governance structure to focus on priority-driven decision making and streamlined collaborative governance.

Space Portfolio Management Group: The first step to doing this, is to morph the existing Air Force S&T Group/Board, the Applied Technology Council for Space, and the S&T ExCom into a Space Portfolio Management Group. As discussed in Section 5.1.5, this group should be chaired by the PDSA, and should have responsibility for reviewing all space S&T portfolios and investment decisions. Further, it should have authority for funding of all demonstrations and industry funding projects.

In this group, each investment decision should be predicated on the answers to the following questions:

- How does this support the enterprise priorities?
- How does this align with the acquisition timeline?
- How is this project demonstrating collaboration across mission areas or technology capabilities?

Space Experiment Review Board: Likewise, as discussed in Section 5.1.6.1.1, the SERB process can be modified today to require all experiments be centrally reviewed, and to align launch decisions with the same priority scheme highlighted above.

5.3.2 Phase 2: Model Scope & Acquisition

The first critical step toward the transition to the MBSE approach is to conduct the CNA in one mission area. To do this, a trailblazer team will need to be established, with participation for each of the stakeholders' organizations, combined with a team of MBSE experts to establish the framework for the MBSE tool and a process map for how the CNA and roadmapping processes will flow. This trailblazer team will be led by the AFSPC/CA and report to the PDSA. This team must identify what basic building blocks in the MBSE tool need to be established to facilitate the entire process, and what areas will be unique or populated by the CNA WG and RWG for each mission area.

Once the scope of the MBSE approach is well understood, an acquisition decision will have to be made about the development and maintenance of the MBSE tool prototype. There are both FFRDC and industry contractors using MBSE and supporting the government with various tools. The PDSA and the AFSPC/CA will need to determine how the MBSE approach will be funded and maintained.

Regardless of who develops the MBSE tool baseline, the trailblazer team will be critical to establishing and testing the process. As a baseline for the development of the tool, the existing AFSPC/CC priorities can be captured as the desired functional capabilities in the model. As each mission area completes the CNA, those priorities may be replaced by the new priorities developed using the use case analysis. None of the existing priorities should be removed from the model, unless they are incorporated in the new functional capabilities, or consciously determined to be unnecessary by the CNA Working Group.

5.3.3 Phase 3: Mission Area #1 Prototype

Capability Needs Assessment: When the trailblazer team is satisfied that the MBSE tool is ready for the first official use, then a CNA working group should be established to conduct a prototype model for a single mission area. The CNA will be executed through each of the following steps:

Step 1: Define Use Cases
Step 2: Develop Activity Diagrams to Describe Desired Capabilities

Step 3: Translate Activities into Functional Capability Needs & Define Interfaces
Step 4: Decompose into Top Technology Needs & Attributes
Step 5: Design Structure Matrix to Identify Dependencies
Step 6: Prioritize Technology Needs & Functional Capabilities within Mission Area

Regroup: The trailblazer team should be observers and/or participants in the first mission area CNA, so that any issues or improvements to the process can be documented and resolved after the first CNA is complete, and the prototype can be fully developed for future operational use.

Technology Roadmapping: The Roadmap Working Group for the first mission area can then be established and begin aligning the CNA results with the projected acquisition timelines. The acquisition community should be prepared in advance to provide as much information to the trailblazer team as possible, so that the framework for the roadmap can be developed in the MBSE tool prior to the RWG meeting. The RWG should be a forum for discussing the information, and verifying the established data in the model is accurate, complete, and consistent with all stakeholders' perspectives. Once the RWG is in agreement about the timeline itself, it should then focus on linking the technology needs to the roadmap milestones.

Regroup: Again, the trailblazer team will likely collect main lessons learned through this process that can be applied and modified for the full operational model and use in the next mission area.

Prioritization: The AFSPC/CA will only have one mission area's priorities to consider at this point, so there will not be an enterprise priority list to develop yet. The AFSPC/CA should be working closely with the trailblazer team to ensure the MBSE tool will support this function.

Communicate Priorities & Roadmap: This function will be the first test of the established security procedures for transferring model segments between classification levels, and for displaying different viewpoints of the model in a web portal. The objectives from this initial mission area will be:

1) Establish standard security procedures for future iterations of the PAP
2) Establish the appropriate viewpoints for all stakeholder needs
3) Train stakeholder users to manipulate and use model through web portal
4) Collect feedback from stakeholders about missing data, products, or artifacts that would allow them to replace their own existing processes with use of this model

Sell, sell, sell! Before expanding the model to other mission areas, the PDSA will need to take the product on a road show, to demonstrate the process and products that will be generated through the use of the model. As the space R&D community is realigning and rethinking its processes to focus on enterprise priorities, this tool needs to be promoted and well understood to prepare the community for the transition to its use.

Where to Begin: So the real question is, which Mission Area should go first? We could go easy, and begin with a smaller, simpler area to test the process, or we could go hard, to fully develop the most challenging aspects of the tool. My recommend is to go hard, and start with Space Protection, which will capture a complex ground & space architecture with various levels of classification. Despite its incredible complexity, work has been done in the last few years through the Space Portfolio Reviews and through roadmapping efforts in the Space Superiority Systems Directorate that can be used and built on to establish the MBSE tool. This is also a good place to begin, because it is the highest priority mission area right now, with senior leader, Congressional, and White House attention. The MBSE products and integrated roadmap will help us align our investments and thoroughly consider the tradespace, and will help us explain and justify our investment decisions for the future.

Finally, this mission area is likely to be very highly connected to other mission areas moving forward, that having this area captured first in the MBSE tool will allow for easier consideration and integration when we begin adding other mission areas. As other mission areas go through the DSM process, and analyze the relationships between their functional capabilities and those in the Space Protection area, they may discover important interfaces and needs that are absent today but should be a high priority in the future.

5.3.4 Phase 4: R&D Project Models

Project Model Template: Once the mission area model prototype has been fully flushed out, the trailblazer team should have a clear understanding of what the template for proposed projects will need to include. For the mission area already complete, the technology needs should have specific performance objectives already identified and established as parameters in the model. For other mission areas, the performance attributes will remain text-based data blocks until specific objectives and parameters are established. At a minimum, the template will be a method for capturing the following data about each 6.3 project, and each experiment seeking a launch opportunity.

- Which priorities does it link to?
- Mission areas supported
- Cost
- Schedule
- Risk
- Experiment status (PDR, CDR, etc)
- R&D organization
- Intended transition
- Performance
- ***If space-based, meeting the SERB:***
- Hosted payload or freeflyer?
- Size
- Weight
- Power
- Spaceflight needs (orbit, etc)
- Potential hazards

This template should be tool-neutral, and either defined in an interface document for machine-to-machine ingestion, or templates should be developed with common MBSE tool-vendors for use across the DoD.

Project Model Incorporation: The Space Portfolio Management Group and the SERB should each set specific implementation deadlines for all projects to be considered in the future. After these dates, these groups will no longer accept paper-based documentation for investment decisions.

This will be the first step for the Portfolio Management Group to have formatted data to use for portfolio-wide analysis against the existing priorities.

5.3.5 Phase 5: Finalize Model and Expand to other Mission Areas

This is the rinse and repeat stage, when we start with the CNA for a second mission area with the fully operational model, and take the mission area all the way through the process. As each mission area is added, the library of technology needs will grow, and the DSM capturing the relationships between technology needs and functional capabilities will become more complex.

As the capabilities and information in the model grow, we must continue to align the governance processes as described in Section 5.2. As each mission transitions to the new PAP, the previous Capability Collaboration Teams should be disbanded, and oversight for these mission areas should transition away from the existing governance to these new working groups.

Chapter 6 Conclusions and Future Work

6.1 Conclusions

Today's R&D environment is not taking full advantage of the tremendous research happening throughout the country that could benefit our DoD Space Enterprise. Gen Hyten and the current senior leadership have made great strides in trying to develop and communicate clear priorities for the future, and isolated mission areas are working hard to develop roadmaps and plans for their future acquisitions. But the enterprise as a whole has much room for improvement. The challenges will be many, but the benefits associated with this recommend approach will address the three biggest challenges facing the unique space R&D environment today- the governance structure, the lack of development planning, and the stovepiped mission areas.

First, by streamlining the governance structure under a single space authority, executed by AFSPC, we can morph the many existing decision making processes into one integrated body, with inputs and collaboration from all stakeholders. Through the use of an MBSE approach, supplemented by DSM analysis and common roadmapping techniques, we can facilitate this new governance structure with a shared repository of information and analysis.

This recommended approach also allows for a clear, structured technology maturation plan that fully incorporates the needs of all mission areas and assists decision makers in setting priorities based on acquisition needs and technology dependencies.

Further, with the approach outlined in this recommendation, we can begin to break down the barriers between stovepiped mission areas, and make decisions that are best for the enterprise as a whole, versus best for a single mission area.

Overall, the recommended tools and process improvements described will result in bettering the DoD Space Enterprise:

- Communication
- Centralized control, decentralized execution
- Optimized decision making
- Dependencies and synergies
- Open-Systems Architecture
- Coordination
- Collaboration
- Cooperation

Because this will all be accomplished using existing methods and tools, this solution could be implemented immediately, in the phased approach described. Not only will it better align the R&D process for the DoD Space Enterprise, but it will drive a new evolution of systems engineering practices throughout the aerospace industry.

6.2 FUTURE WORK

There is still room for work to be done to further these recommendations. Most of this work would be best conducted by the DoD with specific MBSE and subject matter experts to advance the concept to a level where it can be contracted and implemented. The specific areas for further investigation include:

1) ***Prototype model development:*** Although this MBSE approach has been demonstrated in several similar functions, albeit different applications, a prototype model for the specific functions described here should be developed prior to finalizing the path for implementation.
2) ***Security classification solution:*** The integration of a model across multiple classification levels is possible, but challenging, and needs to be carefully planned with a cybersecurity specialist and MBSE expert for resolution.
3) ***Governance tools & activity review:*** To truly consolidate the existing governance as described, a thorough review of the tools used and activities performed should be conducted to ensure the new collaborative governance achieves the correct functions. This would most easily be done by a person with support from senior leadership and access within the Department.
4) ***Timelines for model implementation***: After items 1 and 2 above are complete, a realistic timeline for model development and implementation could be developed.
5) ***Timelines for governance transition:*** After items 3 and 4 above, a realistic transition plan could be developed to align the on ramp of model tools with the consolidated governance structure.
6) ***Funding considerations:*** One area that has not been addressed here, is how the funding structure might change in the future to better align the decision making. One area for future exploration would be to examine the pros and cons of the Navy's use of a Working Capital Fund to fund the NRL.

Each of these areas could be examined from an academic perspective, but would more appropriately be conducted at the direction of senior leadership to pursue the implementation of the recommendations in this thesis.

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