A Technical and Policy Needs Analysis for Space Traffic Management of Low Lunar Orbit

by

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Abstract

The number of artificial objects in space has grown exponentially in the last decade, encouraging a greater focus on space safety and sustainability. Much of this focus is on the detection, tracking, cataloguing, and coordination of objects in space, also known as Space Traffic Management, which serves to prevent collisions in orbit. The cost of a collision in space is often very high–loss of mission, loss of societal support, or even loss of life. Beyond geosynchronous orbit, the Artemis mission brings a renewed excitement for lunar operations, and many countries plan to send missions to the moon in the coming decades. As this topic is quite future-looking, there are many gaps in research related to lunar Space Traffic Management. This thesis serves to begin filling these gaps by answering if Space Traffic Management will be necessary for low-altitude selenocentric orbits. This thesis analyzes the likelihood of collisions in Low Lunar Orbit using NASA's General Mission Analysis Tool and a GRAIL-based gravity model with 70 x 70 degree and order to propagate selenocentric orbits. These propagations are run using high performance computing through the MIT SuperCloud. Methods of preventing collisions are discussed with propagation analysis conducted. A discussion on recommendations on which satellites should maneuver if both have the capability is provided. Analysis found that impulsive burns are viable solutions to avoiding collisions. This thesis also serves to promote proactive development of a Space Traffic Management system for Low Lunar Orbit by discussing five main policy questions focused on the sustainability of Low Lunar Orbit. For each of these questions, the current solution used around Earth is given, followed by a discussion of the possible solutions that could be implemented in Low Lunar Orbit.

Thesis Supervisor: Daniel E. Hastings
Title: Cecil and Ida Green Professor in Education

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A final note: The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, United States Space Force, Department of Defense, or the U.S. Government.

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Chapter 1

Introduction

The number of artificial objects in space has grown exponentially in the last decade [1], encouraging a greater focus on space safety and sustainability. Much of this focus is on the detection, tracking, cataloguing, and coordination of objects in space, also known as Space Traffic Management. U.S. Space Policy Directive-3 defined Space Traffic Management to "mean the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment" [2]. All the tasks listed above serve a common goal of preventing collisions in orbit. The cost of a collision in space is high. First, there is loss of expensive technology, often on the order of millions to billions of U.S. dollars. There is loss of mission, which can have crippling effects on the functioning of modern society. Finally, a collision creates a massive debris cloud putting all satellites in range at risk. A worst-case scenario, theorized by Donald Kessler, involves a collision inciting a chain reaction of subsequent collisions littering the orbital regime with so much debris it becomes inaccessible [3].

Beyond geosynchronous orbit, the Artemis mission brings a renewed excitement for lunar operations, and many countries plan to send missions to the moon in the coming decades. As of 2022, only three countries had landed objects on the moon. Within the next decade, this number may triple [4]. In 2021, PwC released a report that projected the lunar market to reach a cumulative $170 billion by 2040 [5]. It will be imperative to protect these assets and the lives of the humans on the surface and in orbit.

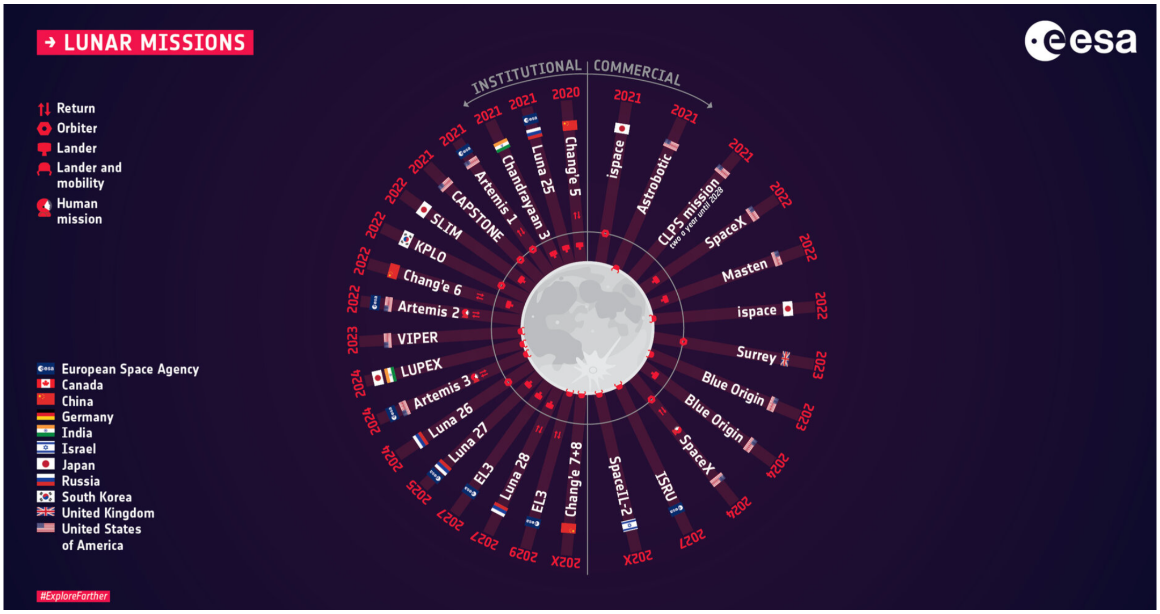


Figure 1-1: Lunar Missions Overview [6]

The goal of this thesis is to provide a technical and policy analysis to suggest what should be done surrounding Space Traffic Management and sustainability of Low Lunar Orbit. The sustainability discussion surrounding Earth orbit is split around preventing further damage and acting to remove debris endangering current and future satellites. Ideally, the latter will not be required for selenocentric orbits.

1.1 Space Traffic Management: History and Current State

The idea of managing objects in space, such as managing automobile traffic or air traffic, was conceptualized before ever actually sending anything to space. Writers began theorizing the need for space law and space traffic rules, suggesting that we pull from similarities in air law regulation to develop such regulation for space. However, these suggestions remained just ideas for over half a century. While it made sense in concept, people did not actually see a need to regulate space traffic because it was relatively unpopulated and space is big. Debris was quite minimal, and people believed that their satellites were safe. However, even a population of just two satellites possess some risk of colliding.

Collisions in space are hypervelocity impacts. According to the European Space Agency, such impacts, even with objects just millimeters in diameter, can be treated almost as explosions as the kinetic energy is so high [7].

While satellites move fast, governments typically don't. Ten years after a French satellite was struck by a piece of space debris, the world began conducting official studies on Space Traffic Management. Decisions and improvements were not completed fast enough, as just three years later, in 2009, the United States' Iridium 33 satellite collided with Russia's Cosmos 2251 satellite, creating a massive debris cloud. The collision occurred without any prior warning [8]. In similar cases, a warning with great uncertainty is not very useful.

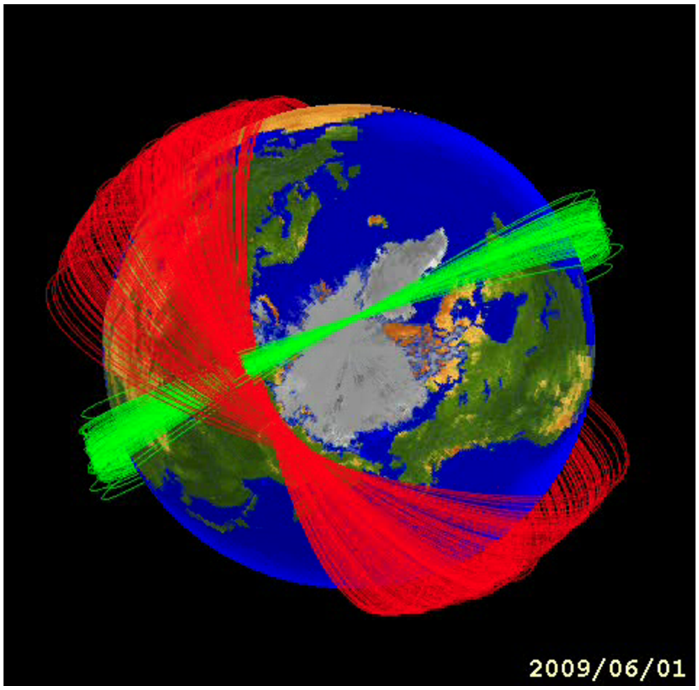


Figure 1-2: Tracked Debris Cloud 4 Months after the Collision of Iridium 33 and Cosmos 2251 [9]

The United States then tasked the 18th Space Control Squadron with the Space Situational Awareness sensor tasking mission. This Air Force Squadron, now the 18th Space Defense Squadron in the Space Force, is responsible for detecting, tracking, and identifying all objects orbiting Earth. The 19th Space Defense Squadron runs conjunction analyses on the catalog maintained by the 18th to predict if satellites have any risk of collision. If a satellite in Low Earth Orbit has a one in ten million chance of colliding with an object, the Squadron will notify the owner/operator of the satellite [10]. There are different standards of when to notify based on the orbit the satellite is in and the sensor that collected the data. For deep space objects, the squadron monitors and provides warnings to objects that are predicted to come within five kilometers of each other. For near earth objects, the Squadron monitors and provides warnings to objects that are predicted to come within one kilometer of each other. Deep space object positions are propagated out ten days in advance, while near earth object positions are propagated out five to seven days in advance. This difference is due to accuracy as well as warning time needed to prepare and plan a maneuver.

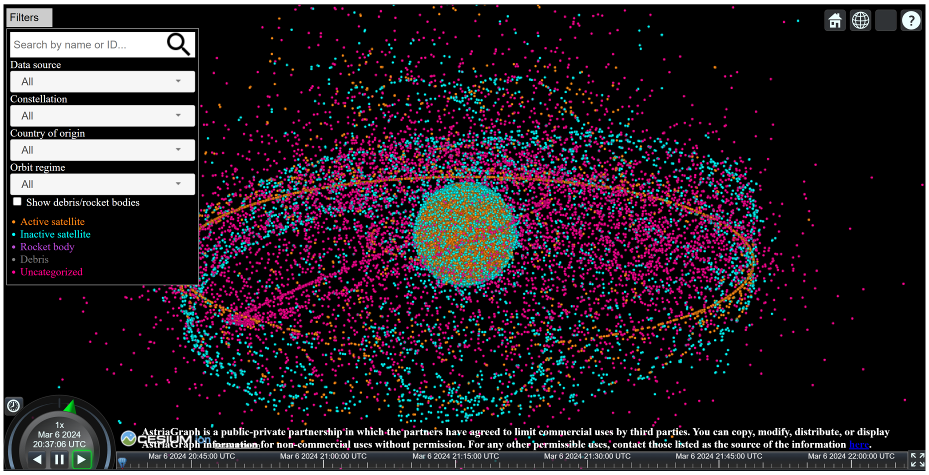
Table 1.1: Reporting Criteria for Conjunction Warnings in SFS Handbook [10]

Basic Reporting Criteria		
	Space-Track Criteria	Emergency Criteria
Notification Method	Conjunction Data Message	Conjunction Data Message and Close Approach Notification email
Deep Space	Time of Closest Approach $\leq$ 10 days and Overall Miss $\leq$ 5 km	Time of Closest Approach $\leq$ 3 days and Overall Miss $\leq$ 5 km
Near Earth	Time of Closest Approach $\leq$ 3 days and Overall Miss $\leq$ 1 km and Probability of Collision $\geq e^{-7}$	Time of Closest Approach $\leq$ 3 days and Overall Miss $\leq$ 1 km and Probability of Collision $\geq e^{-4}$

In recent years, other countries have created their own Space Situational Awareness programs. This is done not just in effort to improve the system, but also with hopes to achieve strategic autonomy [11]. Europe recently opened its collision avoidance service. Similar to the United States, the Space Situational Awareness system first relied entirely on military sensors. European Union nations lack the sensor quality, political financial support, and experience with Space Situational Awareness and Space Traffic Management, so many international partnerships were pursued [12]. The European Union Industry and Start-ups Forum on STM now works to acquire and integrate commercial assets and data into its Space Traffic Management system [13].

Historically, Russia is the only other country with an experienced and robust Space Surveillance System, though this is likely to change in the coming years. The United States and Russia have relatively similar systems and methods, as they resulted as a sort of byproduct from missile warning systems. Additionally, the two countries are the original main actors in space.

Russia maintains a large database of information that is shared, much like the United States [14]. This information has been interpreted and visualized on platforms such as Astriagraph [15], founded by Moriba Jah, an astrodynamicist and ardent proponent of improved collaboration in Space Traffic Management and space sustainability. It is important to note that visualizations often do not have the satellites to scale.



Data source: All
Constellation: All
Country of origin: All
Orbit regime: All
☐ Show debris/rocket bodies

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Figure 1-3: Home Screen of Astriagraph Website [15]

Like the European Union, the United States is moving its Space Traffic Management operations from the military sector to the civil sector. This move was a main topic in Space Policy Directive-3 [2]. This separation will allow for decreased classification of systems and increased data and methods sharing on an international level. Currently, China does not share data from its Space Situational Awareness sensors. International collaboration is expected to increase in all things space, especially Space Traffic Management, so many are hopeful that more countries will join the effort.

There are also companies, such as LeoLabs and Slingshot Aerospace, that have made business cases of Space Traffic Management, even though the United States Space Force provides this service for free. LeoLabs uses radar to track satellites and objects in space in Low Earth Orbit [16]. Slingshot uses optical methods to track satellites and objects in space from Low Earth Orbit out into cislunar space [17]. These companies admittedly have very tough competition: their own government. However, their biggest competition is also their largest customer. As the United States conducts the Space Traffic Management role switch from the military to the civil sector, these companies have found the perfect opportunity to enter the market. These companies do not provide collision warnings to everyone, rather they solely focus their tracking and propagation on their customer's satellites. The data is still compared to large universally shared database position data for conjunction analysis, but the dedication of resources the company can provide to singular satellites or constellations increases the confidence in the position of the satellite. This then decreases uncertainty in collision probability.

European companies are also entering the market. Three European companies—Neuraspace, Ienai Space, and Endurosat—plan to test and demonstrate a collision avoidance system in the coming years [18]. Neuraspace is a Space Traffic Management company based in Portugal that runs on the platform "Focus on fewer alerts with more time to manoeuver, with a scalable AI/ML solution [19]." Ienai Space is a Spanish company that creates different types of thrusters for use in space [20]. EnduroSat is a satellite manufacturer based in Bulgaria [21]. These companies, along with others, are collaborating to prove the need and the benefit of integrating European companies into the Space Traffic Management mission. The demonstration hopes to prove out the capability of using artificial intelligence to automatically avoid collisions without operator input.

For the most part, the current Space Traffic Management system gets the job done—actual collisions are extremely rare. Yet, satellite operators and developers are still unhappy with the current state of Space Traffic Management. The current method of Space Traffic Management has many flaws, and it is unbelievably criticized by essentially all users. On the Neuraspace website, they argue that "traditional collision avoidance requires disruptively large amounts of time and manpower to protect hundreds of satellites" [19]. While not actually new, many see Space Traffic Management as an emerging field. This is because the technology and methods need to be revisited. Additionally, Space Traffic Management was regarded as relatively unimportant for many years. Richard DalBello, the director of the United States Office of Space Commerce, outlined five challenges he sees within Space Traffic Management: Space Situational Awareness technology shortfalls in the form of sensor confidence and debris removal, international woes in terms of communication and sharing of responsibility, improving Space Situational Awareness without harming the growth of the commercial sector, regulation of non-traditional activity in space, and determining appropriate commercial space operator responsibilities [22].

With the space industry rapidly growing, the number of people wanting to change the status quo of Space Traffic Management grows, too. In the past decade, the space industry has grown at an unprecedented rate. According to Neuraspace director Chiara Manfletti, "the amount of conjunction alerts in critical orbits has soared five times in recent years as record numbers of satellites are sent around the Earth" [18]. This has changed the domain greatly, and it severely increased the need for a proper and efficient Space Traffic Management system. Moreover, Space Traffic Management is seen as necessary to encourage and protect economic growth in space. As we see an increase of operations around the Moon, space actors will need to consider Space Traffic Management systems that operate beyond near-Earth space.

1.2 The Moon

1.2.1 Environment

The orbital environment surrounding the Moon is quite different from the near-Earth environment. First, the Moon has no atmosphere except a very thin, weak exosphere that does not cause notable drag, thus making lower altitude orbits possible. Meteorites, satellites, and debris do not burn up before hitting the lunar surface, which complicates satellite disposal and poses risks to surface missions. Additionally, there are no clouds or weather effects, aside from solar weather, that would affect communication. The radius of the Moon is 1738 kilometers, compared to the Earth's radius of 6378 kilometers. The mass of the Moon is 1.2% of the Earth's mass.

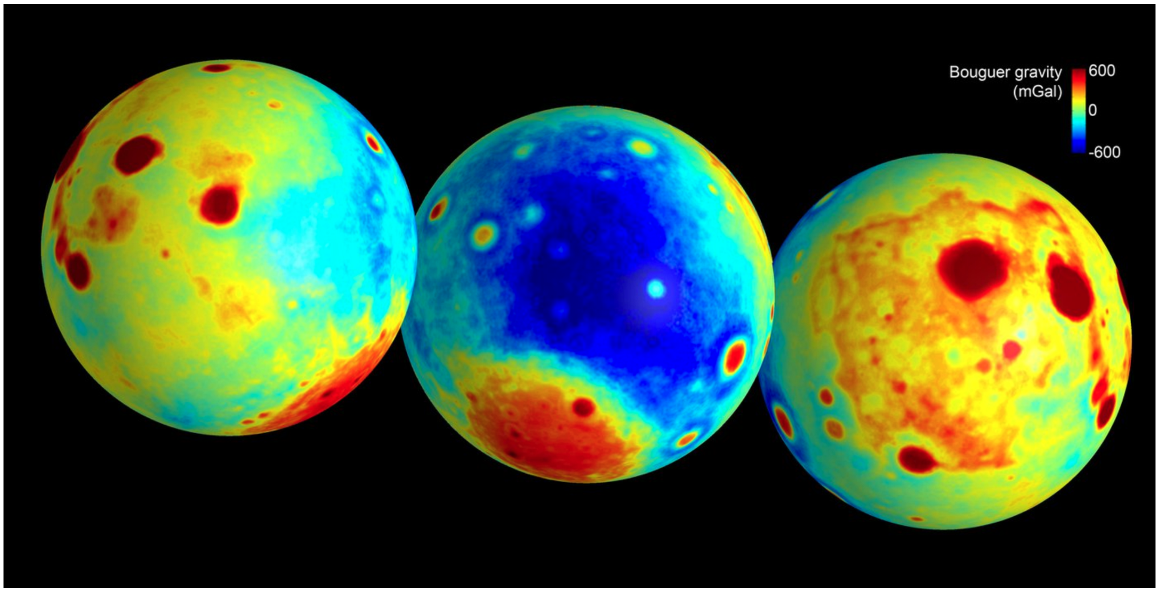


Figure 1-4: Bouger Gravity Map of the Moon from NASA's GRAIL Mission [23]

Next, selenocentric orbits do not experience regular, uniform gravity. Figure 1-4 shows the Bouger Gravity map of the Moon, which shows gravity anomalies. The average gravity experienced on the surface of the Moon, about 1.62 meters per second squared, would be reflected as zero in Bouger gravity. For scale, the average gravity experienced on Earth's surface is 9.81 meters per second squares. The unit used in the figure is milligal. For reference, 1 meter per second squared is 100,000 mGal.

The Moon's gravity is far from uniform. It has numerous mascons, short for mass concentrations, that are regions with a strong gravitational pull [24]. Orbits closer to the moon face stronger effects from the uneven gravity field. At altitudes of 100 kilometers or lower, known as Low Lunar Orbit, most orbits are unstable and will crash into the surface eventually, without the help of any drag forces. However, due to the locations of the mascons, NASA scientists have reported that there are four inclinations at the low altitudes that are stable: 27, 50, 76, and 86 degrees [25]. At higher altitudes, the satellites begin experiencing stronger third-body effects from other bodies in our solar system, such as the Earth, the Sun, and Jupiter.

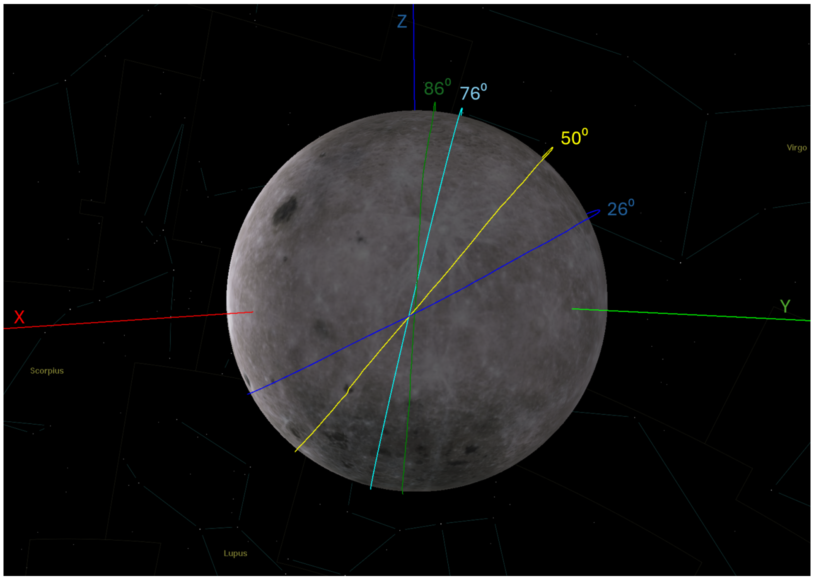


Figure 1-5: Frozen Inclinations in Low Lunar Orbit

Satellites also move slower around the Moon relative to how they move around the Earth. In Low Lunar Orbit, the average velocity of a satellite is about 1.5 kilometers per second, compared to an average of 7.8 kilometers per second in Low Earth Orbit. A bullet travels at about 1 kilometer per second. Due to the speed of satellites, even in Low Lunar Orbit, a 100 kilogram satellite has a kinetic energy of over 100 megajoules. Thus, at both orbital speeds, collisions are undesirable and could be catastrophic.

Other differences include an almost negligible magnetic field, which provides satellites with less radiation protection than is seen around Earth. The Moon does, however, receive radiation shielding from the Earth's magnetic fields for a small part of the month with certain geometries. Radiation is harmful to both humans and technology, as it can cause irreversible health damage as well as burn out electronics. Additionally, a much smaller problem that comes from the lack of a magnetic field is the inability to use magnetic torque rods for attitude control.

As the Moon is 384,400 kilometers away from Earth, there is a one-way communication delay of about 1.3 seconds, which is not something to be ignored, yet it is an acceptable delay for most mission scenarios. As a result of being tidally locked with the Earth, the far side of the Moon is "totally shielded from the Earth's electromagnetic noise and is—electromagnetically at least—probably the quietest location in our part of the solar system" according to the Lunar Planetary Institute [26]. Missions would require a relay satellite to communicate with the far side of the Moon. There are also lower amounts of electromagnetic noise around the Moon in general due to its distance from Earth and limited amount of active communications.

1.2.2 Past, Present, and Future

The first flyby of the Moon was in 1959, and the first manned landing occurred just ten years later [27]. Almost 100 Moon missions were attempted before the 1980s by the United States and the Soviet Union, only to have not a single mission occur during the 80s [28]. Robotic missions returned in the following decades as other nation-states entered the territory. Humans have not been to the Moon since 1972.

In 2019, the Chinese landed a rover on far side of the Moon [29]. The Artemis program began with Artemis 1 successfully launching and completing its mission in 2022. The Artemis Accords have been signed by 39 nations (as of April 2024) and will serve as an initial step in guiding how the world approaches operations on and around the Moon.

In the 2020s, the space community is seeing a surge of proposed lunar missions. There will not only be an increase in orbiters and landers, but there are expected to be humans from multiple countries on the lunar surface within a decade [30] [31]. According to NSR's Moon Market Analysis, over 250 lunar missions are set to launch within the next ten years, and the market is set to generate about $105 billion [32].

There are ongoing lunar efforts in over 80 national space agencies as well as several private companies. Much of the initial missions, aside from the expected science missions, will serve to test and develop necessary infrastructure for operations, such as communications and position, navigation, and timing (PNT). Thus, now is the time to also begin considering Space Traffic Management architectures.

Chapter 2

Technical Needs Analysis

The forces used in all modelling are described under the Conjunction Model Methodology. The Conjunction Model is built assuming there are no maneuvers in order to determine what the worst case would be without any collision avoidance. In making decisions about maneuvering and collision avoidance, it is assumed that there will be a sufficient PNT system for Low Lunar Orbit. There are ongoing programs looking to support this, with tests that have already proven accuracy to less than 100 meters (ESA) [33]. According to a working group in the Space Use Subgroup of UNOOSA, lunar PNT will rely on Global Navigation Satellite Systems (GNSS) from Earth, such as GPS, and a future Lunar GNSS constellation [34]. Sufficient PNT will allow for greater confidence in the location of satellites, which will inevitably decrease the number of conjunction warnings. The data has been analyzed for both the 5 kilometer range and the 1 kilometer range. If the orbital propagation is very good and position confidence is high, the range required to run a sufficient conjunction analysis is low. Thus, if every satellite knows its position within 100 meters, and the propagation is known to be very accurate, the 1 kilometer range for conjunction warnings may be sufficient.

Low Lunar Orbit refers to the orbital region up to an altitude of 100 kilometers. This region will likely host satellites that support ground missions as well as missions studying the Moon. It will also be a staging orbit for landers. As it is a relatively small region that is expected to be quite populated, it will be the focus of this research.

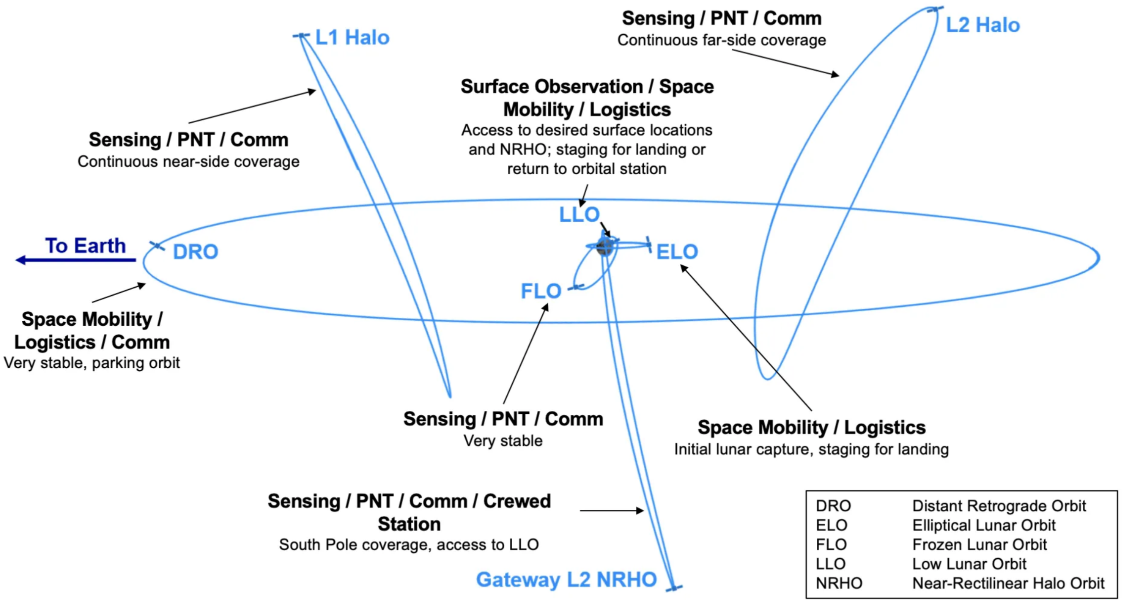


Figure 2-1: Selenocentric Orbits [35]

This analysis of the technical needs for Space Traffic Management in Low Lunar Orbit serves to answer numerous questions. Is a Space Traffic Management system necessary for selenocentric orbits? How often would we expect satellites to come near each other? Can impulsive burns be used to avoid collisions? To answer these questions, a Conjunction Model is created and a Maneuver Analysis is conducted.

2.1 Conjunction Model

As owner-operators are notified when their satellites are expected to come within a certain distance of another satellite, this model served to determine how often satellites in selenocentric orbits can be reasonably expected to come within 5 kilometers and 1 kilometer of each other.

2.1.1 Methodology

This model serves to analyze the likelihood of collisions in Low Lunar Orbit. The selenocentric orbits are propagated using NASA's General Mission Analysis Tool (GMAT) [36]. According to NASA, GMAT is "the world's only enterprise, multimission, open source software system for space mission design, optimization, and navigation," which "supports missions in flight regimes ranging from low Earth orbit to lunar, libration point, and deep space missions" [36].

GMAT requires quite active participation in the creation of the model, which is beneficial to understanding what forces are being applied to the spacecraft you are propagating. This model used a GRAIL-based gravity model with 70 x 70 degree as recommended in a study by Kim et al funded by the Korea Aerospace Research Institute [37]. It takes into account third-body effects from the Earth, Mars, Sun, and Jupiter. Following recommendations in the GMAT User's Guide, the model uses the numerical integrator PrinceDormand78 to propagate the orbits [36]. If the satellites impact the surface, they are removed from the orbital regime and the simulation continues. The satellites are propagated for 10 days, as this is typically the propagation duration used for deep space objects by the 18th Space Defense Squadron [10]. The model checks for surface impacts about every ten minutes.

In order to determine trends, a multitude of simulations were run in groups of 50, 100, 150, and 200 satellites, first randomly distributed and then weighted for projected high population areas, such as polar orbits and frozen orbits, which are particularly stable inclinations in Low Lunar Orbit. These frozen orbits exist primarily for near circular orbits at inclinations of 26°, 50°, 76°, or 86°[25]. The weighting was as seen in Figure 2-2.

There is a higher weighting on 86°, as many missions are expected to be in polar orbits to support the Artemis mission [38]. Additionally, many planned missions, such as NASA's Lunar Trailblazer and China's Chang'e 7, intend to study and map the surface, so they will be in low-altitude polar orbits to get adequate surface coverage. There is limited information on expected orbit parameters of future missions, so the above numbers reflect an assumption on the approximate future distribution of inclinations used in Low Lunar Orbit.

The randomly distributed satellites are constrained to the following ranges of orbital elements: an altitude between 10 and 100 kilometers, an inclination between 0 and 90 degrees, an eccentricity less than or equal to 0.000001, an argument of

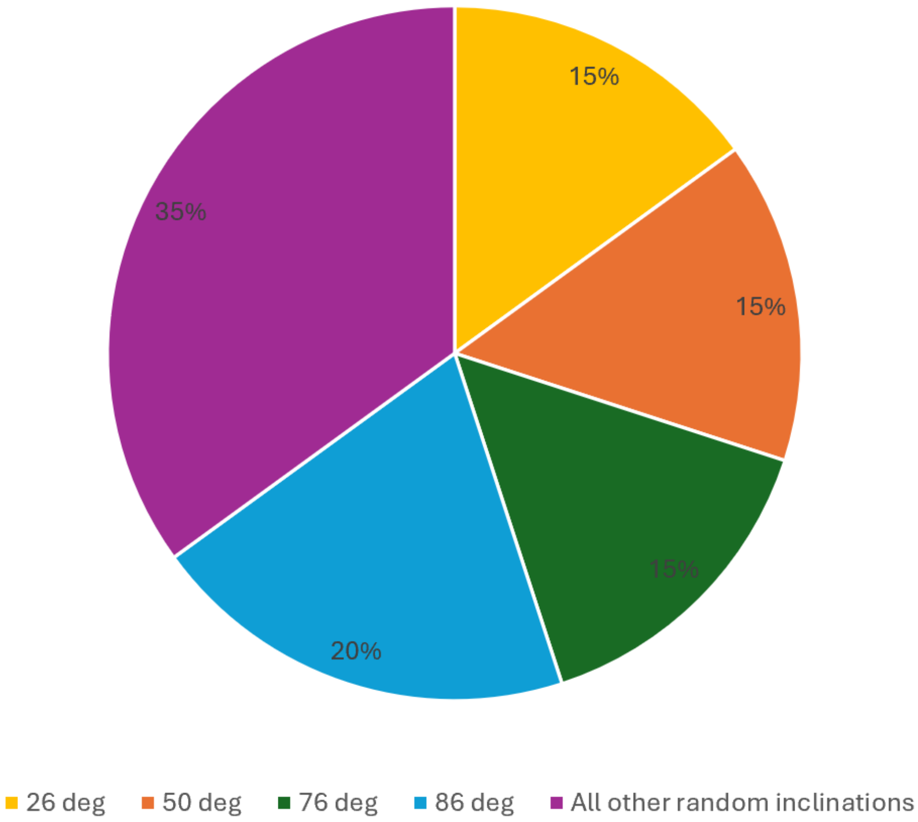


Figure 2-2: Distribution of Inclinations used in Model

periapsis between 0 and 360 degrees, and a right ascension of the ascending node between 0 and 360 degrees, and a true anomaly between 0 and 360 degrees. The altitude limits are chosen with the lower bound based on the lowest feasible stable orbit and the upper bound being the limit of Low Lunar Orbit. The tallest mountain on the Moon has a peak altitude of about 5.5 kilometers. The eccentricity is chosen to be near circular as these orbits are known to be more stable (such as to include the frozen orbits) and will likely be more desirable.

After the simulations are complete, analysis is done to study the frequency of which these satellites come within various distances of each other. This is done using a Python script that conducts simple vector distance calculations using Equation 2.1.

$$\vec{Distance} = \begin{bmatrix} x_{Sat1} \\ y_{Sat1} \\ z_{Sat1} \end{bmatrix} - \begin{bmatrix} x_{Sat2} \\ y_{Sat2} \\ z_{Sat2} \end{bmatrix} \tag{2.1}$$

These vectors come from position files of the satellites output by the propagator. This was used to determine how often satellites come within 5 kilometers of each other and 1 kilometer of each other. These distances were based on the reporting criteria in the Spaceflight Safety Handbook for Satellite Operators used by the 18th Space Defense Control Squadron. The 5 kilometers represents the deep space distance, and the 1 kilometer represents the near earth distance from the Basic Reporting Criteria for the 18th Space Defense Squadron [10]. The 1 kilometer distance is likely more applicable to Low Lunar Orbit if the positional accuracy is similar or better than the accuracy in Low Earth Orbit. This is reliant on the eventual shift to a lunar PNT system.

Multiple actions were taken to increase the ease of computing. First, the simulations are run using high performance computing through the MIT SuperCloud [39]. This greatly decreased the run time and simplified running multiple simulations in parallel. To run one simulation of 200 satellites took about an hour on SuperCloud, compared to eight hours on a personal computer. SuperCloud also provided the ability to run eight simulations at once. Additionally, once the model was tested, a MATLAB script was used to generate script files for GMAT. This allowed for randomization in the orbit parameters as well as the creation of thousands of satellites across hundreds of scripts. Once the simulations were done, the position files of all satellites could be downloaded from the SuperCloud storage for processing.

2.1.2 Results

While running the simulations for each type of data set, it was found that 40 trials of each simulation was sufficient. After 40 trials, there is little change in the average number of collisions (less than 1) or the variance with the addition of 10 more trials. The statistics of the results can be seen in Table 2.1. The full results can be seen in Appendix B.

Table 2.1: Statistics of Conjunction Data from Model

Conjunction Data (5 km)								
	Unweighted Inclinations				Weighted Inclinations			
Number of satellites	50	100	150	200	50	100	150	200
Mean	2.45	10.33	25.65	44.35	2.45	11.48	25.672	47.65
Variance	4.55	21.52	44.43	49.43	2.85	14.15	52.07	89.83
Maximum	7	18	45	58	7	25	42	65
Minimum	0	0	15	29	0	3	16	26
Conjunction Data (1 km)								
	Unweighted Inclinations				Weighted Inclinations			
Number of satellites	50	100	150	200	50	100	150	200
Mean	0	0.1	0.08	0.13	0.05	0.1	0.15	0.3
Variance	0	0.09	0.12	0.11	0.05	0.09	0.18	0.26
Maximum	0	1	2	1	1	1	2	2
Minimum	0	0	0	0	0	0	0	0

As expected, simulations with weighted frozen inclinations tend to have a higher number of collisions due to the proximity and crowding of the frozen inclinations. The mean number of conjunctions for a 1 kilometer distance was expected to be noticeably lower than the mean for a 5 kilometer distance. However, the means for 1 kilometer are surprisingly low, with all of the mean results being at or under 0.3 conjunctions in the 10 day period. This is a big difference from the 5 kilometer distance average, which is over 44 for both groups of 200 satellites.

It is also interesting that, for 50 satellites, the unweighted inclinations case and the weighted frozen inclination case had the exact same mean for the 5 kilometer distance. The true difference lies in the variance. The weighted inclinations case saw half the number of trials with 0 conjunctions than the unweighted case (4 trials compared to 8).

Based on the data, the only case in which one might be able to make an argument for no need of Space Traffic Management is if there are 50 or less randomly distributed satellites. Random distribution is highly unlikely. Once you begin preferring certain inclinations or other orbital parameters, or you add more satellites, you run the risk of expected conjunctions. Just one conjunction, especially at the 1 kilometer distance, is enough to warrant a Space Traffic Management system.

It is important to note that there were a few outliers in the data. These outliers always contained one or two pairs of satellites with very similar orbital parameters came within 5 or 1 kilometer of the other very consistently. Numbers seen included 309 conjunctions at 5 kilometers for 150 satellites, 674 conjunctions at 5 kilometers for 200 satellites, and 124 conjunctions at 1 kilometer for 200 satellites. All three simulations included the weighting on frozen inclinations. These large outliers were never seen for the unweighted scenarios, though it would not be impossible. The nature of weighting certain inclinations increased the likelihood of such outliers, though they were still rare, happening about once in forty trials. These data points were removed after ensuring that a small change in the initial right ascension of the ascending node ($\pm 2^\circ$) or inclination ($\pm 0.5^\circ$) of one of the satellites would result in an expected magnitude of conjunctions. Additionally, it can be expected that a registration authority would not approve satellites on such trajectories nor would owner/operators allow their satellites to be at risk so many times in 10 days.

The lunar month, 29.53 days, and year, 365 days, were additional time scales tested, though for far fewer trials. For the month, there were 5 trials of 50 satellites and 3 trials of 100 satellites. For a year, there was 1 trial of 50 satellites. This limited number of trials was due to run time as well as a desire to search for anomalies. The purpose was not to fully understand longer-term dynamics and conjunction data.

At these time periods, more satellites became unstable without any station-keeping maneuvers. The number of satellites still orbiting at the end of the time period implies that the rest of the satellites impacted the surface of the Moon. The results can be seen in Tables 2.2 and 2.3.

One of the month-long simulations saw the exact mean of satellites still orbiting at the end of the simulation. These satellites were further investigated. Out of 31

Table 2.2: Conjunction Data from Year-long Model

Conjunction Data (5 km)	
50 satellites	
Number of Conjunctions	37
Satellites still orbiting at end of year	17

Table 2.3: Conjunction Data from Month-long Model

Conjunction Data (5 km)	
50 satellites	
Average Number of Conjunctions	3.6
Average number of satellites still orbiting at end of month	31
100 satellites	
Average Number of Conjunctions	22.3

surviving satellites, 27 were in frozen inclinations. Of the 19 that crashed into the surface, 10 were not in frozen inclinations. Those in frozen inclinations that did crash were evenly distributed between the four inclinations. This indicates that while the frozen inclinations are noticeably more stable than other inclinations, there may be additional factors affecting stability of spacecraft in these inclinations.

Again, just one collision would be enough to justify some level of Space Traffic Management because of the stakes of a collision in Low Lunar Orbit. An accuracy of 0.5 kilometers for orbital position would mean that the conjunctions at 1 kilometer would matter, and the number of conjunctions expected is incredibly low. At 2.5 kilometer accuracy, the number of conjunctions that would occur without intervention or proper planning increase substantially. Even if the number of collisions would be incredibly low, this data shows a need for good positional accuracy.

Satellites in Low Lunar Orbit will come close to each other often. Better situational awareness decreases the number of conjunction warnings issued, but this number is unlikely to be zero for much longer.

2.2 Maneuver Analysis

The maneuver analysis model serves largely to confirm that impulsive burn maneuvers are a viable solution to avoiding collisions in Low Lunar Orbit. The use of electric propulsion may also be an option. However, this is not explored in this analysis.

2.2.1 Methodology

The maneuver analysis utilizes data and methods from the Conjunction Model. The identical forces and methods of propagation are used. To study the effects of maneuvering on conjunction warnings, tests are run on multiple sets of satellites that have known expected conjunctions. These pairs of satellites come from conjunctions seen in the Conjunction Model data.

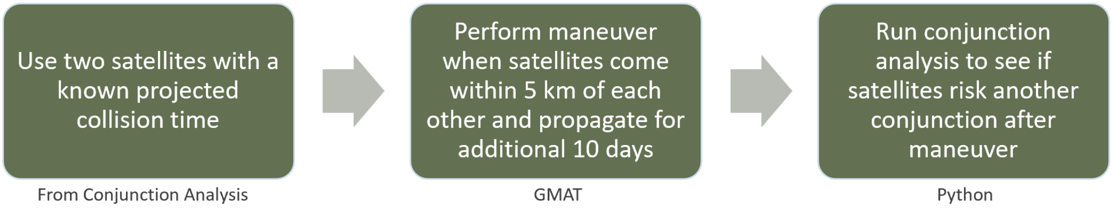


Figure 2-3: General Process Flow of the Maneuver Analysis

The general process of the maneuver analysis, along with the software used for the step, can be seen in Figure 2-3. All maneuvers tested are impulsive burns. Each pair of satellites is tested with a specific set of test maneuvers. These tests are designed to mimic reasonable maneuver decisions, as well as to test a span of options to see if there are trends of more efficient maneuvers. These tests include one satellite maneuvering and both satellites maneuvering. Both satellites will be tested with identical maneuvers in the scenarios in which only one satellite moves.

The maneuvers tested will intend to change either altitude or the right ascension of the ascending node. The altitude change will affect semi-major axis and eccentricity of the orbit. Large changes of eccentricity in Low Lunar Orbit are often what cause satellites to crash into the surface. Thus, this is be monitored.

All burns are done in the Velocity-Normal-Binormal (VNB) coordinate frame. The V component is in the direction of the satellite's velocity. The N component is the "instantaneous orbit normal" [40], which is perpendicular to the orbital plane traditionally on the positive Z side of the plane with respect to the Moon. The B component completes the right-handed set, most often by pointing directly away from the Moon. This is especially true for this work, as most of the orbits are near-circular.

To change the altitude using the VNB coordinate frame, the delta-v is solely in the Binormal direction. A positive delta-v would result in an instantaneous increase in altitude.

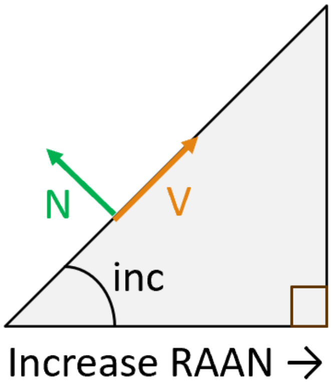


Figure 2-4: Increasing RAAN in the VNB Coordinate Frame

To change the right ascension of the ascending node using the VNB coordinate frame, the delta-v is a combination of the Velocity and the Normal component. This can be seen in Figure 2-4. The goal is to get a horizontal vector, with respect to the figure. Thus, Equation 2.2 shows the resulting delta-v as a function of the inclination would be, where a is a scaling factor for the amount of delta-v desired.

$$\vec{\Delta v} = \begin{bmatrix} a * cos(inclination) \\ a * -sin(inclination) \\ 0 \end{bmatrix} \tag{2.2}$$

The maneuvers are automated, so if the satellites come within 5 kilometers of each other, a maneuver will be conducted. This could mean multiple maneuvers during the propagation. However, the type of maneuver and amount of delta-v used in each maneuver is constant throughout each propagation.

After completing a maneuver, the satellites continue with the 10 day propagation. The position files are run through the Python script to determine how many conjunction warnings, at 5 kilometers and 1 kilometer, are experienced over the 10 days. A full success would mean the maneuver resulted in zero conjunction warnings. A partial success would mean the original conjunctions are avoided, but few, new conjunctions occur later in the propagation. A failure would mean that the original conjunctions are not avoided, or more conjunctions are created than the original.

The time delay of later conjunctions is recorded, and the distance of conjunctions post-maneuver is compared to the distances of the original conjunctions. The satellites will also be monitored to see if any maneuvers result in the satellite crashing into the surface.

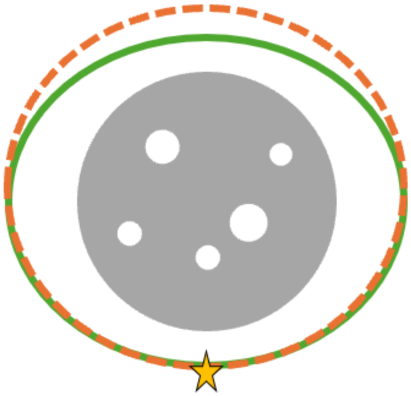


Figure 2-5: Diagram of Burn Location for Orbit Changes

All cases tested a single burn. It would take at least two burns to return to the original orbit. In Figure 2-5, the green line represents the original orbit. After a burn at the yellow star, the resulting orbit would be the orange orbit. To return to the green orbit, the satellite would need to perform another burn at the yellow star. This is not tested in this analysis. Thus, the satellite would stay in the resulting orange orbit for the rest of the simulation.

These burns do not take into account the amount of fuel burned or the mass or size of the satellites. Distance measurements are from point-mass center of masses. If multiple conjunctions are within the same time series (i.e. one conjunction lasting for more than one time step, up to two minutes), it is counted as just one conjunction.

2.2.2 Results

Because the maneuver is initiated when satellites cross the 5 kilometer mark, the first conjunction is not completely avoided. However, in the cases in which there are multiple time steps for the first conjunction, it is seen in most cases that the miss distance at the second time step is larger than it was without the maneuver. This indicates avoidance.

For altitude change maneuvers, a delta-v of 100 meters per second consistently made the orbits too elliptical and resulted in the satellite impacting the surface of the Moon. This is expected, as the average maneuver around Earth is about 10 meters per second, and velocities are slower around the Moon compared to Earth. As expected, the results mirrored each other depending on which satellite did the burn. For one satellite, increasing altitude prevented all further collisions while decreasing altitude did not prevent further collisions. The opposite was consistently seen for the other satellite. Burns with a delta-v of 10 meters per second and 1 meter per second were successful.

For RAAN changes, the results were similar in that what worked for one satellite tended to complement what worked for the other satellite. Unlike with altitude, a delta-v with a magnitude of 100 meters per second did not make the orbits unstable. This is because the maneuver did not contribute significant changes to eccentricity.

In testing maneuvers with a magnitude of 100, 10, and 1 meter per second, there was no magnitude that consistently failed. All trials were case dependent. However, many of the trials were full successes, specifically 100 meters per second and 10 meters per second.

Chapter 3

Policy Needs Analysis

3.1 Literature Review

3.1.1 International Law

Outer Space Treaty

The Outer Space Treaty [41], more formally known as the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies", opened for signatures and entered into force in 1967 [42]. It served as the first international treaty focused on operations in space, and it is still being ratified by countries to this day. The United Nations cites the Outer Space Treaty as outlining the following basic principles on activities in space [42]:

> - "the exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all mankind;
> - outer space shall be free for exploration and use by all States;
> - outer space is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means;
> - States shall not place nuclear weapons or other weapons of mass destruction in orbit or on celestial bodies or station them in outer space in any other manner;
> - the Moon and other celestial bodies shall be used exclusively for peaceful purposes;

> - astronauts shall be regarded as the envoys of mankind;
> - States shall be responsible for national space activities whether carried out by governmental or non-governmental entities;
> - States shall be liable for damage caused by their space objects; and
> - States shall avoid harmful contamination of space and celestial bodies."

All of the above principles are related to this research. Though, these guidelines are left quite broad. Many terms are left undefined, such as contamination and peaceful purposes. This leaves the principles up to the interpretation of the actor. This treaty is well cited, but not perceived as a strict guiding document due to its age and vagueness.

Moon Agreement

The Moon Agreement, more formally known as the "Agreement Governing the Activities of States on the Moon and Other Celestial Bodies", was adopted by the United Nations General Assembly in 1979, but did not enter into force until 1984 [43]. When referencing the Moon, this document indicates that it is also referring to orbits around the Moon. Article 3 reemphasizes that the Moon "shall be used by all State Parties exclusively for peaceful purposes" [43]. Moreover, it bans the establishment of military bases, though military members can conduct peaceful scientific research. The document highlights a push for international cooperation "on a multilateral bases, on a bilateral basis, or through international intergovernmental organizations" [43]. Article 5 reads,

> "1. State Parties shall inform the Secretary-General of the United Nations as well as the public and the international scientific community, to the greatest extent feasible and practicable, of their activities concerned with the exploration and use of the moon. Information of the time, purposes, locations, orbital parameters and duration shall be given in respect of each mission to the moon as soon as possible after launching, while information on the results of each mission, including scientific results, shall be furnished upon completion of the mission. In the case of a mission lasting more than sixty days, information of conduct of the mission, including any scientific results, shall be given periodically, at thirty-day intervals. For missions lasting more than six months, only significant additions to such information need be reported thereafter.
>
> 2. If a State Party becomes aware that another State Party plans to operate simultaneously in the same area of or in the same orbit around or trajectory to

> or around the moon, it shall promptly inform the other State of the timing of an plans for its own operations.
>
> 3. In carrying out activities under this Agreement, States Parties shall promptly inform the Secretary-General, as well as the public and international scientific community, or any phenomena they discover in outer space, including the moon, which could endanger human life or health, as well as of any indication of organic life."

This article is quite interesting in general, especially in terms of Space Traffic Management. If we assume good knowledge of orbital positioning, which is a realistic assumption given current PNT testing and results, then all State Parties of the Moon Agreement would be required to report their orbital parameters, per Article 5 Section 1.

Other later articles are also concerned with information sharing and collaboration, which is perhaps why the three largest space actors, Russia, China, and the United States, are all not Parties of the Agreement [44]. There are other experienced space actors that are signatories or Parties to the Moon Agreement, such as France, Australia, and India, so the treaty does still bear importance in international relations and actions around the Moon. However, without the U.S., Russia, and China, it is seen as a rather weak and unsuccessful law.

Registration Convention

The Registration Convention, more formally known as the "United Nations Convention on Registration of Objects Launched into Outer Space", entered into force in 1976 [45]. This document served to assist in the identification of objects for safety in space as well as ease the assignment of responsibility in the event of an accident. The main content of this convention is found in Article 4 [46], which lists the information that must be reported to a space object registry when launching an object into space:

- name of launching State or States;
- an appropriate designator of the space object or its registration number;
- date and territory or location of launch;
- basic orbital parameters, including:
  - nodal period;

    - inclination;
    - apogee;
    - perigee;
- general function of the space object.

It also indicates that States may provide updates from time to time. Contrary to the Moon Agreement, this treaty was signed by Russia and the United States and acceded by China, as well as numerous other States [47].

There are critiques of this treaty, such as a lack of incentive for "non-independently space-faring nations" and lack of sanctioning mechanisms [48]. Despite this, the registration requirements have been met for a majority of objects in space. However, there remains to be unregistered objects in space [49]. The United Nations reports that, as of 22 January 2024, "approximately 87% of all satellites, probes, landers, crewed spacecraft and space station flight elements launched into Earth orbit or beyond have been registered with the Secretary-General" [50]. This number is strikingly low considering how early the Registration Convention came into effect. There are motivations, such as military operations or national defense purposes, for States to not register certain satellites. Yet, the registration of only certain satellites diminishes the purpose of the catalog creation. As amateur astronomers have easier access to information sharing on the internet and social media, there is even less reason to not register basic information for all satellites.

Guidelines for the Long-term Sustainability of Outer Space Activities

The Guidelines for the Long-term Sustainability of Outer Space Activities [51] were written by the Committee on the Peaceful Uses of Outer Space and adopted in 2019. It is important to note that the guidelines are not law and thus are voluntary suggestions on behavior. The document then encourages States to implement mechanisms to encourage or force compliance within their country. More technically capable States should practice and encourage stronger adherence to the guidelines and promote international cooperation. The idea of cooperation is at the forefront of this document.

The document defines long-term sustainability of outer space as "the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations" [51]. The guidelines are split into four topic areas. These topics and their associated guidelines can be seen below:

- Policy and regulatory framework for space activities
    1. Adopt, revise and amend, as necessary, national regulatory frameworks for outer space activities
    2. Consider a number of elements when developing, revising or amending, as necessary, national regulatory frameworks for outer space activities
    3. Supervise national space activities
    4. Ensure the equitable, rational and efficient use of the radio frequency spectrum and the various orbital regions used by satellites
    5. Enhance the practice of registering space objects
- Safety of space operations
    1. Provide updated contact information and share information on space objects and orbital events
    2. Improve accuracy of orbital data on space objects and enhance the practice and utility of sharing orbital information on space objects
    3. Promote the collection, sharing and dissemination of space debris monitoring information
    4. Perform conjunction assessment during all orbital phases of controlled flight
    5. Develop practical approaches for pre-launch conjunction assessment
    6. Share operational space weather data and forecasts
    7. Develop space weather models and tools and collect established practices on the mitigation of space weather effects
    8. Design and operation of space objects regardless of their physical and operational characteristics
    9. Take measures to address risks associated with the uncontrolled reentry of space objects
    10. Observe measures of precaution when using sources of laser beams passing through outer space
- International cooperation, capacity-building and awareness
    1. Promote and facilitate international cooperation in support of the long-term sustainability of outer space activities

    2. Share experience related to the long-term sustainability of outer space activities and develop new procedures, as appropriate, for information exchange
    3. Promote and support capacity-building
    4. Raise awareness of space activities
- Scientific and technical research and development
    1. Promote and support research into and the development of ways to support sustainable exploration and use of outer space
    2. Investigate and consider new measures to manage the space debris population in the long term

The guidelines never mention Space Traffic Management. Nevertheless, as one of the main purposes of Space Traffic Management is space sustainability, nearly all of the guidelines are related to Space Traffic Management, especially the section *Safety of space operations*. Effectively preventing collisions dramatically reduces space debris, as collisions create massive debris clouds that can trigger further collision events.

Space weather is mentioned multiple times, as it is one of the largest uncontrollable threats to satellites. Space weather can cause reversible or irreversible damage to satellite, including total electrical failure [52].

Dealing with defunct satellites is not something anyone has great experience in, though it is an active research topic to this day. In 2021, China was able to relocate a defunct satellite to a graveyard orbit, an orbit dedicated for disposal, using another satellite as a tow-satellite [53]. Other countries, such as Japan, have been making similar attempts in efforts to clean up Earth's orbital environment [54]. This will be discussed later as a main policy question.

Artemis Accords

The Artemis Accords, subtitled "Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes", was established by NASA in partnership with seven other nations (Australia, Canada, Italy, Japan, Luxembourg, the United Arab Emirates, and the United Kingdom) in 2020. The Artemis Accords are built on the principles outlined in previous UN documents, such as the Outer Space Treaty, the Rescue and Return Agreement, and the Registration Convention. There are currently 39 signatories to the Artemis Accords. Russia and China have not signed the Accords, as of April 2024.

The written purpose of the Artemis Accords is "to establish a common vision via a practical set of principles, guidelines, and best practices to enhance the governance of the civil exploration and use of outer space with the intention of advancing the Artemis Program" [55]. The document reiterates later the intent of the Accords to apply specifically to "civil space activities conducted by the civil space agencies of each Signatory" [55]. The sections in the Artemis Accords that outline expected intent and behavior of Signatories are Peaceful Purposes, Transparency, Interoperability, Emergency Assistance, Registration of Space Objects, Release of Scientific Data, Preserving Outer Space Heritage, Space Resources, Deconfliction of Space Activities, and Orbital Debris. Many of these align directly with topics in the Outer Space Treaty and other early documents, so much so that it specifically encourages nations to accede the Registration Convention. These tenets emphasize the intent and benefit from cooperation, collaboration, and transparency in space exploration.

Though the document requires sharing and publication of scientific data, it does not specify what must be shared. State Parties intend to follow or encourage others to follow the Registration Convention. Under Section 11 – Deconfliction of Space Activities [55], it states

> "5. The Signatories commit to provide each other with necessary information regarding the location and nature of space-based activities under these Accords if a Signatory has reason to believe that the other Signatories' activities may result in harmful interference with or pose a safety hazard to its space-based activities."

which indicates that the Signatories intend not to have constant transparency, but rather to be transparent to an extent when needed. The concept of information sharing when in risk of harmful interference is expanded on in the implementation of safety zones:

> "7. In order to implement their obligations under the Outer Space Treaty, the Signatories intend to provide notification of their activities and commit to coordinating with any relevant actor to avoid harmful interference. The area wherein this notification and coordination will be implemented to avoid harmful

> interference is referred to as a ‘safety zone’. A safety zone should be the area in which nominal operations of a relevant activity or an anomalous event could reasonably cause harmful interference. The Signatories intend to observe the following principles related to safety zones:
>
> (a) The size and scope of the safety zone, as well as the notice and coordination, should reflect the nature of the operations being conducted and the environment that such operations are conducted in;
>
> (b) The size and scope of the safety zone should be determined in a reasonable manner leveraging commonly accepted scientific and engineering principles;
>
> (c) The nature and existence of safety zones is expected to change over time reflecting the status of the relevant operation. If the nature of an operation changes, the operating Signatory should alter the size and scope of the corresponding safety zone as appropriate. Safety zones will ultimately be temporary, ending when the relevant operation ceases; and
>
> (d) The Signatories should promptly notify each other as well as the Secretary-General of the United Nations of the establishment, alteration, or end of any safety zone, consistent with Article XI of the Outer Space Treaty."

This could have interesting implementations. If a satellite in Low Lunar Orbit is supporting an active mission, perhaps supporting astronauts on the ground, would that require a safety zone? Where and how large would the safety zone be? Namely, could all of Low Lunar Orbit be declared a safety zone due to the threat of collision debris harming astronauts upon falling to the surface, thus requiring regular reporting of up to date orbit parameters? It is unexpected that this policy would be misused by Signatories, and it would be expected that the eight original Signatories would regulate the creation of safety zones. Though, it is left quite broad, opening the opportunity for interpretation.

3.1.2 National Law (United States)

Orbital Debris

The United States Government first released the Orbital Debris Mitigation Standard Practices in 2001, and the most recent update was released in 2019 [1]. This update served to make the standard practices easier to implement internationally. The original goal of the Orbital Debris Mitigation Standard Practices defined in the document was to "limit the generation of new, long-lived debris by the control of debris released during normal operations, minimizing debris generated by accidental explosions, the selection of safe flight profile and operational configuration to minimize accidental collisions, and postmission disposal of space structures" [1].

The document has five objectives, under which specific mitigation practices are defined. The five objectives are:

1. Control of debris released during normal operations
2. Minimizing debris generated by accidental explosions
3. Selection of safe slight profile and operational configuration
4. Postmission disposal of space structures
5. Clarification and additional standard practices for certain classes of space operations

Within the thirteen mitigation practices listed underneath these objectives, many standards are defined such as the minimum size of planned debris that must be reported, maximum explosion probabilities, maximum collision probability, and probability of successful postmission disposal. Other topics discussed include, but are not limited to, depletion of energy, proximity operations, and satellite servicing.

In 2004, the Federal Communications Commission (FCC) amended its application for frequency allocation to require disclosure of debris mitigation plans [56]. It cited that the Commission maintained this authority under the Communications Act. The original document, FCC 04-130, then goes through the "Specific Elements of Orbital Debris Mitigation" listed in the Orbital Debris Mitigation Standard Practices published at the time. The information required in the application has since been updated with the Orbital Debris Mitigation Standard Practices.

Space Policy Directive-3

Space Policy Directive-3 was a presidential memorandum issued by President Trump in 2018 with the subject "National Space Traffic Management Policy" [57]. In this memorandum, it declares that "the United States considers the continued unfettered access to and freedom to operate in space of vital interest to advance the security, economic prosperity, and scientific knowledge of the Nation". With mentioning the growing use of space, the memorandum discusses concurrent growth of both the commercial space market and the role of the Department of Defense for protection of assets in space. This leads to the main intent of the Directive, which is stated in the paragraph below:

> "To maintain U.S. leadership in space, we must develop a new approach to space traffic management (STM) that addresses current and future operational risks. This new approach must set priorities for space situational awareness (SSA) and STM innovation in science and technology (S&T), incorporate national security considerations, encourage growth of the U.S. commercial space sector, establish an updated STM architecture, and promote space safety standards and best practices across the international community."

The Directive then goes into detail about what exactly this would entail creating, improving, and/or maintaining. It goes through definitions, principles, goals, guidelines, and roles and responsibilities.

Perhaps the most discussed and remembered part of the entire memorandum is the directive to pass many STM responsibilities over from the Department of Defense to the Department of Commerce. This is a large shift, as the Department of Commerce has very limited experience in this, while the Department of Defense has had almost full responsibility from the beginning. This is largely to take some burden off the Department of Defense, to recognize the changing space market, and to inspire new innovation within Space Traffic Management.

3.2 Main Questions and Possible Solutions

Within U.S. Space Policy Directive-3, a Space Traffic Management framework was listed to consist of "best practices, technical guidelines, safety standards, behavioral norms, pre-launch risk assessments, and on-orbit collision avoidance services" [57]. This thesis will primarily address behavioral norms and best practices with a focus on on-orbit collision avoidance.

3.2.1 How will satellites be discarded?

Earth

The US Orbital Debris Mitigation Standard Practices lists the possible methods of disposal for Earth-orbiting satellites. The preferred methods are maneuvering to complete a direct reentry into Earth's atmosphere or maneuvering into a "heliocentric, Earth-escape orbit". Other methods listed are gradual atmospheric reentry, storage between Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO) in specified graveyard orbits, storage above GEO, direct retrieval, or specific plans for long-term reentry for higher-altitude special orbits.

Atmospheric reentry causes the satellite to break up before ever hitting the surface. The use of graveyard orbits is to organize dead satellites in stable zones far from active operations.

Moon

The Moon does not have an atmosphere like the Earth. It has a very thin atmosphere, more specifically an exosphere [58]. Thus, direct reentry would not result in the satellite burning up, rather, it would crash into the surface. This is still a feasible option, though there would need to be sufficient planning and control in the maneuver. The impact will create a dust cloud, which could negatively affect operations on the surface. It would not be unreasonable to establish one or more satellite graveyards on the surface in optimized locations, such as craters far from places of ongoing or future scientific research. Other groups are already promoting this option [59], especially if the satellites can be retrieved and repurposed.

Maneuvering into a heliocentric Earth/Moon escape orbit is a very reasonable option. The average delta-v required to put the satellite on a heliocentric trajectory from Low Lunar Orbit is around 3 kilometers per second, while doing the same from Earth orbit is near 20 kilometers per second. Admittedly, this is still a high delta-v. However, it would be the preferred option between impacting the surface and sending the satellite on a heliocentric trajectory.

Gradual atmospheric reentry would not be desirable. As previously mentioned, control and placement is very important as the satellites will impact the surface.

The final method used around Earth is storage in graveyard orbits. There is work being done to find similar graveyard orbits for the Moon, though there are not any well known plans for these orbits. It is difficult with the instability of many selenocentric and cislunar orbits. There are of course families of orbits in this area that are known to be more stable, such as Earth-Moon Lagrange points, but these points are rather far away and are expected to be desired places for active satellites [60].

3.2.2 What should be done with defunct satellites?

Earth

A defunct satellite is a satellite that is no longer operating or functioning properly, likely due to a serious failure. Around Earth, not much is done. The Keplerian orbits around Earth are highly predictable and stable, so the satellite is monitored to ensure it does not collide with anything. In the event of a possible collision, the other satellite must move or operators must hope that the collision does not happen. If the satellite is in Low Earth Orbit, it will eventually deorbit and burn up in the atmosphere.

Beyond Low Earth Orbit, it is not as simple. The satellite is just left and monitored. There are companies working to fix this problem through on-orbit servicing, assembly, and manufacturing (OSAM). As previously mentioned, China proved its ability to relocate a defunct satellite from geostationary orbit to a graveyard orbit 300 kilometers above GEO using another satellite as a tow-satellite [53]. Other countries, such as Japan, have been making similar attempts in efforts to clean up Earth's orbital environment [54].

The problem of defunct satellites is being actively researched. It is seen as a big problem around Earth, and it would be an even graver problem around the Moon.

Moon

Around the Moon, you have relatively the same options as around Earth. There are numerous reason why leaving and monitoring the satellites is even less desirable around the Moon. First, Low Lunar Orbit has a greater volume of unstable orbits than it does stable. Additionally, the threat of the satellites uncontrollably crashing into the surface might be a risk people are not willing to take with humans on the surface. However, until further technologies are developed, this may be the most reasonable option. If this is how defunct satellites are dealt with, States may want to pursue stricter regulations on failure probabilities and the like.

The use of on-orbit servicing may be a reasonable option for dealing with defunct satellites in Low Lunar Orbit in the future. As discussed, it is being tested in Earth orbit. Once this technology is fully operational, it could be implemented in the lunar realm. Rendezvous and proximity operations technologies have been used around the Moon, such as the docking of the Apollo lander. It will be tested again with the creation of the Lunar Gateway [61].

There are different way of controlling on-orbit servicing systems. Historically, such as in Apollo or the International Space Station, much of docking operations was done manually, with a human in the loop. There are still systems that use this today, though some systems are switching to autonomous docking. While it can require significant planning, autonomous docking is much cheaper. These systems are being proven successful today and may be necessary for lunar operations. While there may be a presence of astronauts on or around the Moon, it would be logistically complicated to develop a human-in-the-loop on-orbit servicing system to capture defunct satellites. Thus it is imperative to look at autonomous docking.

There are many policy questions already surrounding on-orbit servicing. One of the main topics of debate is whether or not to standardize interfaces for docking. A standard interface can streamline the process of docking and moving the satellites. However, this takes a lot of planning and coordination, as well as potential additional costs that satellite manufacturers do not want as this docking interface may never be needed. Some companies, such as Astroscale, are developing docking systems that do not require a standardized docking interface [62]. Other systems are specifically designed to dock and provide propulsion capabilities to satellites in Geostationary orbit for stationkeeping purposes. It is reasonable to assume that once fully operational, likely within the decade, this technology could soon be transferred to Low Lunar Orbit. If a fleet of these satellites is maintained in Low Lunar Orbit, they could be used as a quick response for removing defunct satellites and sending them on a solar trajectory or strategically crashing them into the surface of the Moon.

3.2.3 Who should move in the event of a potential collision?

Earth

Around Earth, there is no regulation on who has to move. It is simply decided amongst the satellite owner/operators involved. There is nothing against neither or both deciding to move. The responsibility is placed on the owner/operators of the satellites. It is assumed that operators will act in everyone's best interest, as collisions are catastrophic for everyone. Carelessness could also hurt a company's business in the future or even result in lawsuits and fees.

Technically, there is no requirement for operators to even know where their satellite is, and there are current operators that do not. Richard DalBello, head of the U.S. Department of Commerce's Office of Space Commerce, pointed this out while sharing his woes about Space Traffic Management, discussing the need for greater operator responsibility [22].

Moon

Space Traffic Management around the Moon would benefit from greater regulation on collision avoidance. There should be guidelines on who should move, or perhaps even regulation requiring at least one party to move to ensure there is no collision. These regulations could include requirements on satellite capabilities or regulation on operations.

In terms of satellite capabilities, the regulation could be that every satellite must have propulsion capabilities. Many technological regulations benefit from leaving the methods broad to allow for creativity and innovation in solutions. This is the case for a propulsion requirement. There are many solutions that could be reasonable, with the most common current solution of having on-board propellant, either chemical or electrical. Around Earth, there is regulation on the ability to properly dispose of satellites after their mission. This often results in maintaining a certain amount of fuel for end-of-life maneuvers. As previously discussed, if on-orbit servicing is an option, satellites could be refueled or moved. There is a business opportunity in rapid movement of satellites for collision avoidance, along with the movement of defunct satellites. There could also be new methods of moving satellites, such as with lasers from the surface of the Moon, that have not been tested yet.

In terms of regulating operations, this would essentially mean requiring or providing guidelines on how to react to a conjunction warning. Assuming the only method of avoiding collisions is maneuvering, there are three options: one satellite moves, both satellites move, or neither satellite moves.

A reason for having both satellites move would be to split the delta-v required to avoid the collision. Propellant can be expensive, both in terms of money and the mission. However, this would require good advanced notice, planning, and coordination. It may often be found that it is easier to have only one satellite move.

The subsequent question is then "how would you decide which satellite should move?" If both satellites have the capability to move, there are numerous ways to decide who should move. The decision could be based on which satellite would require less delta-v to move, though this will almost always be the smaller satellite. The decision could be based on which maneuver will use less of the satellite's delta-v budget for its mission. The latter is the more ideal scenario; however, it would require calculations and information sharing that some satellite owners may not want to participate in.

The decision on who should move may also amount to who could complete the maneuver in time. Perhaps one satellite has been having communications issues and it is unclear if the maneuver would be successful. It may be the case that one satellite only has electric propulsion, which takes much longer than chemical, and the satellite may not be able to complete a sufficient maneuver in time to prevent a collision.

If the regulation on having a propulsion capability is not in place, there could be one or neither satellite with the ability to maneuver. If only one satellite has the capability, it should be strongly advised or required that the satellite moves. If neither have propulsion capability, then one must hope there is an on-orbit servicing module operational and available to move a satellite. This opens a discussion of who would have to pay for the relocation service. It would most simply be split evenly, regardless of which satellite is moved. Yet, the owner of the moved satellite may be upset that their satellite had to move and not the other satellite. The procedure of deciding who has to move or who should pay should be written into policy, though requiring propulsion capabilities could avoid some of the aforementioned complications.

Finally, if neither satellite has a propulsion capability, and there is no opportunity for relocation by an on-orbit servicer, the only realistic option is to wait and see what happens. This scenario is essentially dealing with two defunct satellites. Due to expected orbit maintenance for Low Lunar Orbits, it is very unrealistic that there would be a satellite without any propulsion capability that is not near end-of-life or defunct.

3.2.4 How should satellites be tracked?

Earth

Various countries and companies track satellites primarily from the surface but also from space. Traditionally, for the United States, the Air Force was responsible for tracking satellites. The Space Surveillance System was used, which combines radar and optical tracking. Now, the Space Force is responsible for tracking, and it uses newly operational Space Fence, a ground-based radar, to help with maintaining Space Domain Awareness [63]. Some satellites have GPS receivers that can help the operators better understand the location of their satellite. Regardless, after taking in data from multiple sensors, the Space Force publishes Two-Line Elements (TLEs) which give information about satellite location but are not accurate enough to run conjunction assessments with [64].

As the United States shifts it's Space Traffic Management mission from the Department of Defense to the Department of Commerce, the Space Situational Awareness mission will see a shift. The Space Force will continue to track and monitor space, but the Office of Space Commerce (OSC), along with NOAA, will be maintaining its own Space Traffic Management system to interface with owner/operators and stakeholders. This system is known as the Traffic Coordination System for Space (TraCSS). The OSC plans to contract out Space Situational Awareness services. OSC named three Consolidated Pathfinder partners in January of 2024, who will provide SSA data and monitoring services for OSC. The partners are COMSPOC, LeoLabs, and Slingshot Aerospace.

Other countries have, or are developing similar technologies, such as the European Union Space Surveillance and Tracking Program [65]. As mentioned, Russia has maintained a Space Surveillance system for decades. Similar methods are used by other countries for detecting and tracking satellites.

Moon

The purpose of this thesis is not to design a system architecture for Lunar Space Traffic Management, though it would be remiss to not mention and discuss the possibilities.

The current method of tracking satellites around the Moon includes both radar and optical, though these methods have challenges when it comes to the Moon. The Moon is 384,400 kilometers away from Earth. Radars deal with something known as the R^4 problem, which essentially means that radar return signal strength diminishes by the distance between the radar and the object to the fourth power. When using optical tracking, there is the obvious issue of needing to have the satellite in view. Of course, this means it must not be behind the Moon when trying to track. It also implies that there must be good lighting on the satellite, which can be quite hard around the Moon. In sunlight, which is usually needed to see the satellite, the Moon itself is bright and will affect the ability to see satellites close to it.

Other methods of tracking include various ranging techniques, such as laser ranging with retro-reflectors, delta differential one-way ranging, or Doppler measurement [66]. These methods are typical for interplanetary missions.

These methods could be continued for tracking objects around the Moon. In fact, it is likely that we will default to these methods for the near future, as other systems have not been developed. However, as the population around the Moon grows, especially in Low Lunar Orbit, these methods may begin to have accuracy problems. If the confidence in location is too low, the problem of excessive conjunction warnings will make its way to Low Lunar Orbit. Thus, orbital tracking and safety around the Moon would benefit from new techniques.

An expensive solution would be to create a localized SSA system on the Moon. Because of the close proximity and lack of atmosphere, tracking data from radars has the potential to be extremely accurate. There would have to be decisions made on where the data would be stored and processed. The time delay to Earth is about 1.3 seconds, which is likely acceptable for receiving data to process. If this model is to be used, for example, around Mars, this delay may be less desirable. At which, localized data processing perhaps through automation may be necessary.

Current missions are working to prove that GPS signals are receivable near the Moon. Though unlikely to happen soon, there have been discussions on creating a lunar GPS system. GPS signals can be used for owner/operators to precisely know the location of their satellite. If deemed necessary, policy could be written to require automated transponders to broadcast location data. This could be used for better confidence in conjunction assessments. There are satellite owners that do not want their location shared, such as certain government or military satellites. Even if a regulation is in place, it is possible such owners do not comply. However, this regulation could be effective on most civil and commercial satellites and would enhance the safety of the orbital environment.

Another option would be to require satellites to be fitted with laser retro-reflectors. This helps with ranging and tracking from far distances. Yet, the real benefit lies with being able to track the satellite even when it is dead or defunct. A GPS transponder would go defunct with the satellite, unless it has its own power source. The laser retro-reflector could be used regardless. This technology faces a similar challenge of some owners likely not complying. However, even moderate compliance would increase the safety of Low Lunar Orbit. It may also improve the speed of on-orbit servicers to be able to locate, dock, and relocate defunct satellites.

3.2.5 Who would be the governing body of a lunar STM system, and who would fund it?

Earth

Around Earth, there is no central global Space Traffic Management System. Law and regulation is primarily localized within countries. The global body that provides some guidance and regulation is the United Nations Office for Outer Space Affairs (UNOOSA), which oversees the Registration Convention. UNOOSA also published the Guidelines for the Long-term Sustainability of Outer Space Activities, which was drafted by the Committee on the Peaceful Uses of Outer Space.

Norms and common interest guide most of the actions and procedures regarding Space Traffic Management. Satellite collisions harm everyone, so being careless is against everyone's interest and could lead to geopolitical tensions. All this to say, there are still actions that are against the norm that go unregulated.

Countries fund their own SSA systems, or benefit from free data sharing. As the commercial sector grows, there will be more contracts and paid services for SSA and STM split between governments and companies.

Moon

Again, the default will likely be to follow the lead of what is done around Earth. There will be no true central body. Norms will guide behavior. Governments will pursue their own data collection, but it will be augmented by commercial providers. These commercial providers will provide general SSA and STM services to all satellite owner/operators in the lunar realm.

This would not be a bad system, if the accuracy of the data is very good. The less confident we are in the data, the more regulation is required to alleviate safety issues caused by low confidence.

In this case, the United Nations Office for Outer Space Affairs should take a pivotal role in organizing committees for setting guidelines and standards. The United Nations is the largest international body, with 193 Member States [67]. While the entire population of Earth is not evenly represented by the United Nations, it is the most widespread and qualified body for international regulation. The work could be modeled after traffic management in other domains, such as maritime. The United Nations has the International Maritime Organization, which is responsible "for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships" [68]. This organization, and similar organizations such as the International Civil Aviation Organization, could be used as models for internation collaboration on traffic management, especially in unowned territory. Additionally, UNOOSA maintains the Outer Space Treaty, the Moon Agreement, and more. Involvement in the sustainability of Low Lunar Orbit should be a priority as more States begin to move operations to the Moon.

Big space actors include the United States, the European Union, Japan, Russia, China, and India, and the list is growing. These States should work to become leaders in establishing the norms around the Moon, or even creating doctrine to guide behavior.

While full compromise can be near impossible on certain issues, the Artemis Accords is a step in the right direction. With 39 countries signed on, it is a first step in cooperating on regulation of modern challenges around and on the Moon. The Signatories should continue to collaborate on establishing norms and policies for lunar operations. They should work to bring these norms and policies to the commercial sector as well, as the Artemis Accords are specifically for the civil sector of each Signatory.

3.3 Final Recommendations

Open communication and transparency will be key in ensuring the safety and sustainability of Low Lunar Orbit. Explicit agreements on behavioral norms should begin happening as soon as possible, as many States seek to send satellites to the Moon within the next decade.

Although there is no true Lunar Space Traffic Management document, there are many historical and current policies, norms, and guidelines that can help frame the conversation. Policymakers should take advantage of what is already written and agreed upon by various countries to have a better chance at reaching compromises.

Discussions on these key policy questions must happen now to provide any chance at a proactive Space Traffic Management system for Low Lunar Orbit. The reasons to be proactive are numerous, and the reasons to be reactive are limited. One collision in Low Lunar Orbit is far too many.

Based on the discussion in this thesis, the following recommendations are made on policy for Low Lunar Orbit:

- The preferred method of satellite disposal should be to send it on a heliocentric trajectory. If there is no other option but to impact the surface, the location should be an internationally agreed upon location to ensure safety of current and future missions.

- All satellites should be required to have propulsion capabilities, whether within the system or through quick-response on-orbit servicing if the technology is available.

- Moving in the event of a conjunction should be highly encouraged. In the event of a collision, the damage done to the usability of the orbital regime should be included in any liability costs.

- The risk of leaving defunct satellites in Low Lunar Orbits is too high. More research should be done in this area. On-orbit repositioning should be explored as a viable option for removing defunct satellites in Low Lunar Orbit.

- Lunar PNT and SSA services should be well-funded to encourage innovative solutions. Increased accuracy in these services greatly improves the safety of the domain.

- UNOOSA should establish a specific organization focused on modern Moon activity. While the Artemis Accords provides a good foundation for norms and international partnership, the United Nations should step in to prevent factions from developing based on alliances.

Chapter 4

Conclusion

4.1 Summary

As the number of satellites around Earth grows rapidly, it is expected that this growth soon spreads to selenocentric orbits, or orbits around Earth's moon. To prevent collisions in Earth orbit, a collective Space Traffic Management system is used to detect and track satellites, propagate forward satellite orbits, and notify satellite operators in the event of a potential collision. The current system is very effective, with almost no accidental collisions occurring. However, this system requires an extensive level of work and has widely agreed-upon grievances, such as too many conjunction warnings at low confidence levels. Without Space Traffic Management, the safety and sustainability of Earth orbit would be in greater question. There could be numerous collisions that create debris clouds inciting further collisions. Space Traffic Management is integral to the continued use of Earth orbit. Currently, there is no organized system for Space Traffic Management around the Moon, as there has been such few satellites orbiting the Moon.

This thesis paper studied the need for a Space Traffic Management system for Low Lunar Orbit. A technical analysis using orbital propagators proved that conjunctions will regularly occur, especially if frozen inclinations are more populated. The summary of results can be seen in Table 2.1. Even 50 randomly distributed satellites will see an average of 2.45 conjunctions in 10 days at a 5 kilometer distance. When

65% of the satellites were in frozen inclinations, the average number of conjunctions increased, as expected. Frozen inclinations are desirable for their stability, so it is likely that there are a majority of satellites in these inclinations. Just 1 conjunction, especially at a 1 kilometer distance is enough to warrant the development of a Space Traffic Management system.

It was also proven that small instantaneous burns can be used to avoid collisions without turning the orbit unstable. Altitude changes and changes in right ascension of the ascending node were the maneuvers tested, and magnitudes of 1 meter per second and 10 meters per second were successful often. Such maneuvers are viable methods of avoiding collisions, if proper warning is given.

There are numerous policies guiding actions in space and around the Moon, but these policies are due for updates. This thesis explored five main policy questions:

- How will satellites be discarded?
- What should be done with defunct satellites?
- Who should move in the event of a potential collision?
- How should satellites be tracked?
- Who would be the governing body of a lunar STM system, and who would fund it?

For each of these questions, the current solution used around Earth was given, followed by a discussion of the possible solutions that could be implemented in Low Lunar Orbit. Policy recommendations provided included, but were not limited to, satellite disposal via heliocentric trajectory, a propulsion capability requirement, funding research on defunct satellite removal, funding development of Lunar PNT and SSA services, and the establishment of a new organization within UNOOSA focused on Lunar activities.

Many lessons can be learned from Space Traffic Management of Low Earth Orbit, both technical and in policy regulation. The international space community should be proactive to develop norms of behavior and technologies that support safety and sustainability in Low Lunar Orbit.

4.2 Future Work

For the Conjunction Model, this process could be used to test other ranges and sets of orbits. To better understand collision risk in the Lunar orbital regime, future research could test orbits with a larger semi-major axis and elliptical orbits. This data set could also be updated to include real mission parameters as more space actors send satellites to orbit the Moon.

Work could also be done to study and predict physical consequences of a collision. More specifically, the dynamics of satellite breakup and the distribution of debris clouds in Low Lunar Orbit could be further researched.

For the Maneuver Analysis, further exploration could study the effects of completing an initial impulsive maneuver, followed some time later by a maneuver back to the original orbit. This would be to maintain the same orbital elements as before, perhaps for mission purposes, but with a shifted true anomaly to prevent the conjunction. Additionally, the use of finite burns, such as with electric propulsion, could be investigated.

For the Policy Analysis, this should continue to be updated as new documents come out. NASA's recent Space Sustainability Strategy [69] touches on many actions related to the recommendations in this thesis. However, Volume 1 explicitly leaves out the lunar/cislunar realm. It is expected that further volumes of this publication will help to inform and motivate sustainability of Low Lunar Orbit.

This field is expected to be active in national and international debates. Further research should be done on lunar graveyard orbits, potential deorbit crash sites, and efficient heliocentric trajectories to better inform decisions made on deorbiting selenocentric satellites and dealing with defunct satellites.

Appendix A

Link to Code

Below is the link to the Github repository with the code used in this thesis:

https://github.com/ckirk04/Conjunction-Analysis-Code

In this repository, there are three files. The descriptions, as well as instructions on use, can be seen below.

A.0.1 main.py

This Python script take the position files of satellites and prints a list of the conjunctions, including the satellites involved, the time step, and the distance between the satellites. It is important that the position files of the satellites have readings at identical time steps. The code is currently set to report all distances less than 5 kilometers, but this can be adjusted.

- Inputs: Folder with satellite position (XYZ) .txt files. The position files should be named "Sat#.txt" where the pound symbol can be replaced with personalized naming convention.

- Outputs: HTML with list of Conjunction Data

A.0.2 maneuver1.script

This script is meant to be run in NASA's General Mission Analysis tool. It propagates two satellites and conducts a burn if they come within a certain range of the each other. This range is adjustable in the Mission Sequence.

The burn is also adjustable. It is written in the VNB coordinate frame, described in this thesis. The units used are kilometers per second.

The point mass third body forces used in this script are Earth, Mars, the Sun, and Jupiter. The gravity field is a GMAT provided GRAIL-based potential and tide file, *grgm900c.cof* and *grgm900c.tide.*

To run this script, upload it to GMAT as the main script file. Adjust the satellite orbital parameters along with other parameters that may need changed, such as the distance tolerance, and run it.

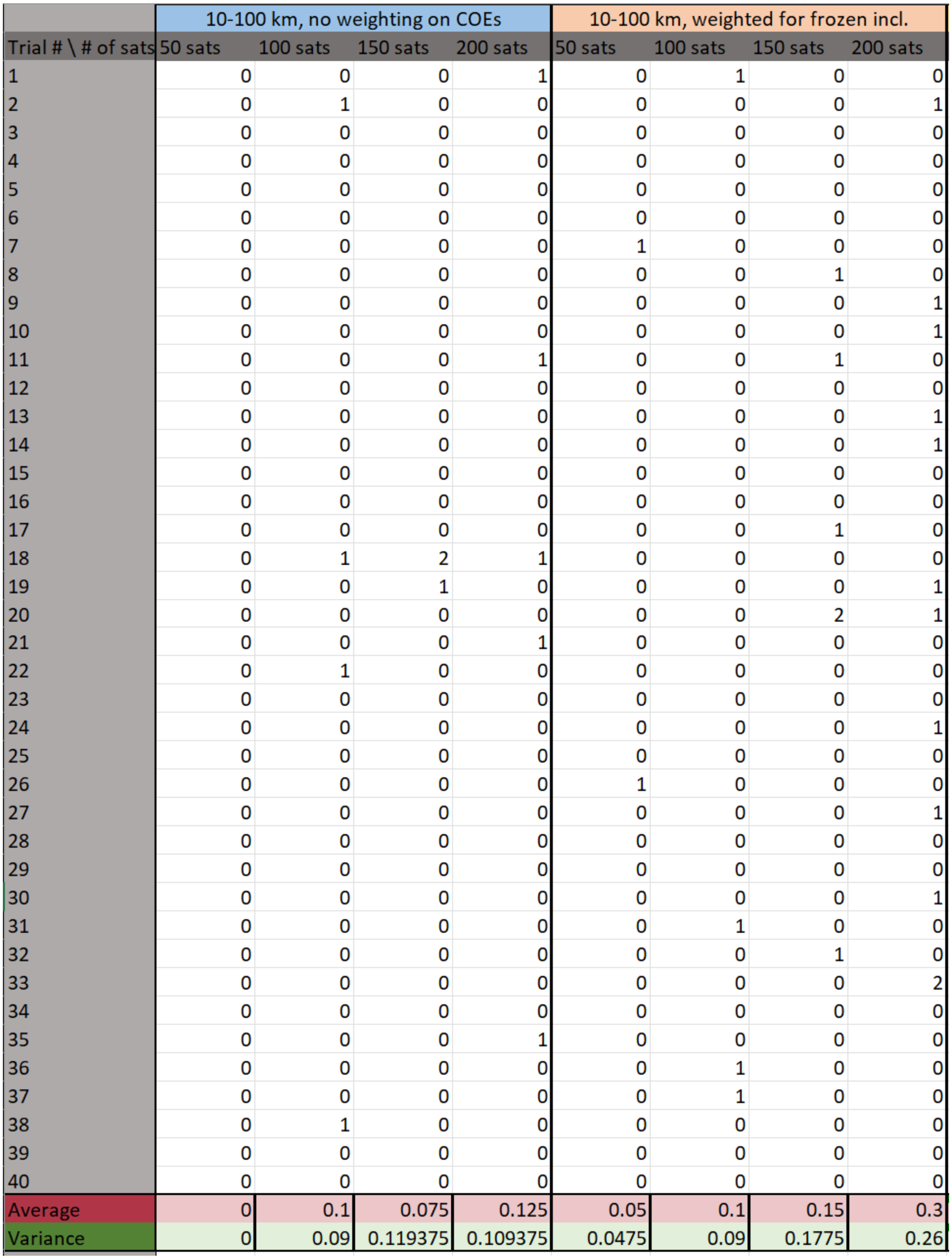
A.0.3 write_GMAT_scripts.m

This Matlab script is used to write many GMAT scripts at once. The top of the file starts loops where you can set the number of scripts you want to write and the number of satellites you want in each scripts. Most of the orbital elements are set to be random, but this can be adjusted.

There are instances of file paths that will need adjusted, such as the gravity files or the file storage of the newly written scripts. This script was specifically written for a Linux-based super computer. At the end of the large loop of the file, there is a commented-out command to run the script in GMAT on the super computer. This could be an option if similar methods are used for running this file.

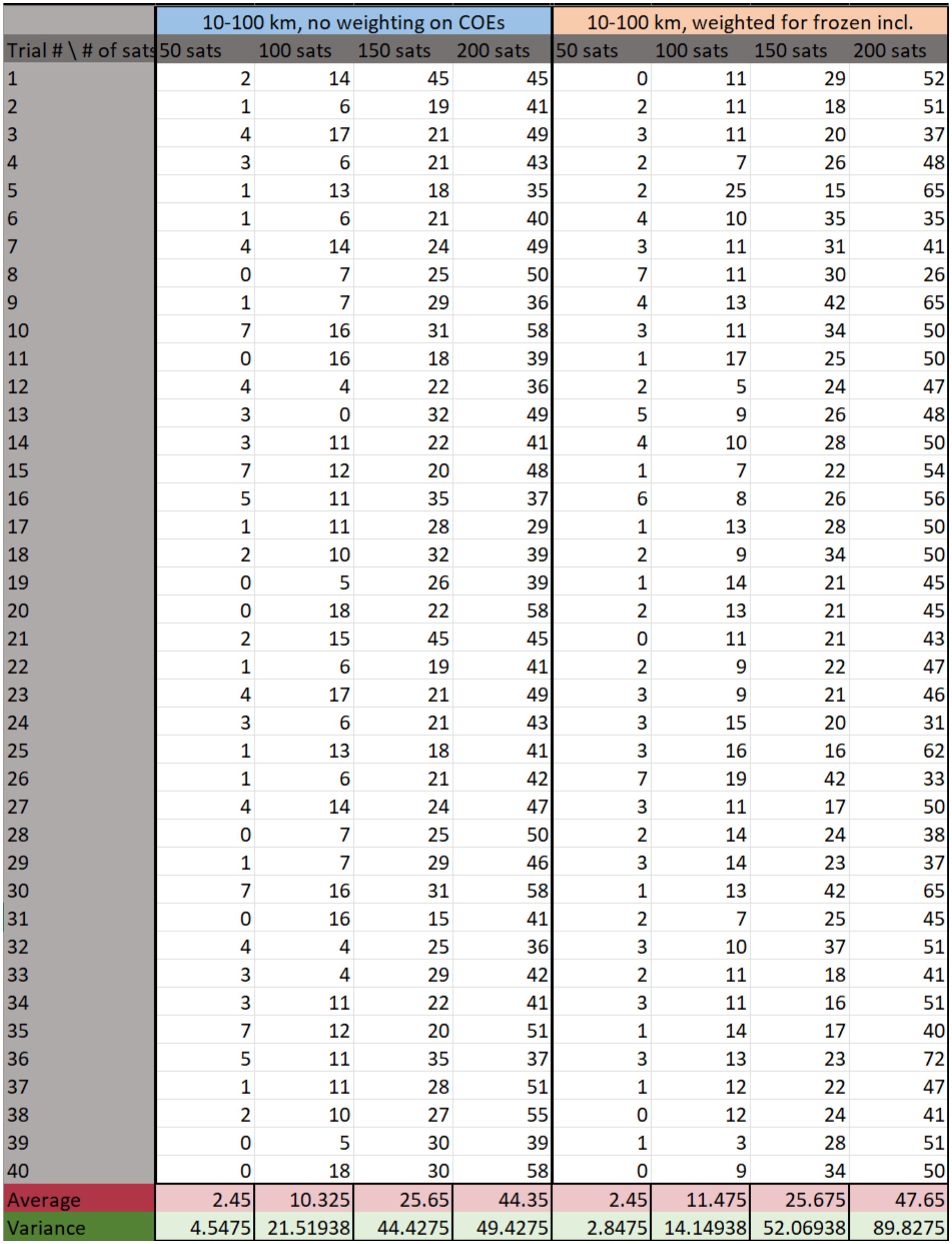
Appendix B

Full Conjunction Data



	10-100 km, no weighting on COEs				10-100 km, weighted for frozen incl.			
Trial # \ # of sats	50 sats	100 sats	150 sats	200 sats	50 sats	100 sats	150 sats	200 sats
1	0	0	0	1	0	1	0	0
2	0	1	0	0	0	0	0	1
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	1	0	0	0
8	0	0	0	0	0	0	1	0
9	0	0	0	0	0	0	0	1
10	0	0	0	0	0	0	0	1
11	0	0	0	1	0	0	1	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	1
14	0	0	0	0	0	0	0	1
15	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	1	0
18	0	1	2	1	0	0	0	0
19	0	0	1	0	0	0	0	1
20	0	0	0	0	0	0	2	1
21	0	0	0	1	0	0	0	0
22	0	1	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	1
25	0	0	0	0	0	0	0	0
26	0	0	0	0	1	0	0	0
27	0	0	0	0	0	0	0	1
28	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	1
31	0	0	0	0	0	1	0	0
32	0	0	0	0	0	0	1	0
33	0	0	0	0	0	0	0	2
34	0	0	0	0	0	0	0	0
35	0	0	0	1	0	0	0	0
36	0	0	0	0	0	1	0	0
37	0	0	0	0	0	1	0	0
38	0	1	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
Average	0	0.1	0.075	0.125	0.05	0.1	0.15	0.3
Variance	0	0.09	0.119375	0.109375	0.0475	0.09	0.1775	0.26

Figure B-1: Conjunction Data for 1 kilometer distance



	10-100 km, no weighting on COEs				10-100 km, weighted for frozen incl.			
Trial # \ # of sats	50 sats	100 sats	150 sats	200 sats	50 sats	100 sats	150 sats	200 sats
1	2	14	45	45	0	11	29	52
2	1	6	19	41	2	11	18	51
3	4	17	21	49	3	11	20	37
4	3	6	21	43	2	7	26	48
5	1	13	18	35	2	25	15	65
6	1	6	21	40	4	10	35	35
7	4	14	24	49	3	11	31	41
8	0	7	25	50	7	11	30	26
9	1	7	29	36	4	13	42	65
10	7	16	31	58	3	11	34	50
11	0	16	18	39	1	17	25	50
12	4	4	22	36	2	5	24	47
13	3	0	32	49	5	9	26	48
14	3	11	22	41	4	10	28	50
15	7	12	20	48	1	7	22	54
16	5	11	35	37	6	8	26	56
17	1	11	28	29	1	13	28	50
18	2	10	32	39	2	9	34	50
19	0	5	26	39	1	14	21	45
20	0	18	22	58	2	13	21	45
21	2	15	45	45	0	11	21	43
22	1	6	19	41	2	9	22	47
23	4	17	21	49	3	9	21	46
24	3	6	21	43	3	15	20	31
25	1	13	18	41	3	16	16	62
26	1	6	21	42	7	19	42	33
27	4	14	24	47	3	11	17	50
28	0	7	25	50	2	14	24	38
29	1	7	29	46	3	14	23	37
30	7	16	31	58	1	13	42	65
31	0	16	15	41	2	7	25	45
32	4	4	25	36	3	10	37	51
33	3	4	29	42	2	11	18	41
34	3	11	22	41	3	11	16	51
35	7	12	20	51	1	14	17	40
36	5	11	35	37	3	13	23	72
37	1	11	28	51	1	12	22	47
38	2	10	27	55	0	12	24	41
39	0	5	30	39	1	3	28	51
40	0	18	30	58	0	9	34	50
Average	2.45	10.325	25.65	44.35	2.45	11.475	25.675	47.65
Variance	4.5475	21.51938	44.4275	49.4275	2.8475	14.14938	52.06938	89.8275

Figure B-2: Conjunction Data for 5 kilometer distance

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