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A Decision Analysis Framework to Consider Space Congestion in Orbit Selection

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A VALUE FRAMEWORK TO MODEL SPACE CONGESTION IN ORBIT SELECTION

THESIS

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Abstract

Low Earth Orbit (LEO) is becoming more congested, which increases the risk to space missions. Decision makers will need to consider this increase in congestion as an increased risk within their mission engineering process. This thesis proposes a methodology to create and implement a value structure that quantitatively scores a range of orbits based on congestion factors of each orbit and how well each orbit meets mission requirements. This thesis demonstrates this methodology on a set of circular LEO orbits defined by altitude and inclination, and scores this illustrative scenario based on notional mission measures and expected number of encounters as congestion measures. These scores are analyzed for sensitivity to changes in orbit scoring recommendations if the decision maker were to change the importance levels between mission and congestion factors. For any given mission definition, this orbit scoring methodology can be used to identify high value orbits that would be critical to controlling space.

I dedicate this work to all the Guardians of the United States Space Force. May your golden horizons be endless. Semper Supra!

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I. Introduction

1.1 Problem Statement

Low Earth Orbit (LEO) is becoming more congested, which increases the likelihood of orbital collisions and thus a potential critical risk to space missions. Congestion also increases the difficulty to distinguish benign activities from illegal or hostile acts. Decision makers will need to consider this increase in congestion as an increased risk within their mission engineering process. This thesis proposes a methodology to create and implement a value structure that quantitatively scores a range of orbits based on congestion factors and how well they meet mission requirements.

1.2 Motivation and Background

The space domain over the last decade has repeatedly been described as a "congested, contested, and competitive environment." Joint Publication 3-14, Space Operations (2018), describes the threat to space as follows:

> Space is a naturally hazardous environment and is increasingly congested, contested, and competitive. Space assets face many threats, both natural and manmade. Natural threats to satellites include solar activity, radiation, and natural orbital debris. Man-made threats can be both unintentional (e.g., satellite debris or electromagnetic interference [EMI]) or intentional (e.g., jamming, lasing, cyberspace attacks, and antisatellite weapons).

This thesis focuses on the "congested" term as used to describe the overall increasingly dangerous density of objects in low earth orbit space.

As space becomes more accessible due to the decrease in launch costs, more valuable as shown by more countries and companies increasing their launch and satellite deployment rates, and more necessary for everyday capabilities, the population of objects on orbit is rapidly increasing. Table 2 and Figure 3 from "LEO Constellation Encounter and Collision Rate Estimation: an Update" (Alfano et al., 2020) depict the anticipated large constellations for 2017-2029 based on FCC and ITU licensing applications. The total number of spacecraft in this list sums to over 57,000. Each launch has multiple pieces of associated debris including, but not limited to, rocket bodies and expended fuel particles. Meteoroids, comets, and asteroids also present a naturally occurring threat of space debris (Seebaugh, 1988).

Catastrophic collisions immediately destroy all mission value of a satellite and other satellites in nearby orbital paths (Kessler and Cour-Palais, 1978). Maneuvers consume limited fuel that reduces the effective lifespan of the satellite. Conjunction analysis warnings require processing time by programmed rules and/or humans depending on circumstance.

More congestion increases the probabilities of collisions, such as the 2009 collision between Iridium 33 and Kosmos 2251. Kessler's syndrome, or collision chain reactions in space, is a well-cited reason for why these orbital collisions cause serious difficulties. These chain reactions are detailed in Kessler and Cour-Palais (1978) and La Vone (2013). While space is vast and the probability of a Kessler incident is small, as more congestion occurs, the likelihood increases.

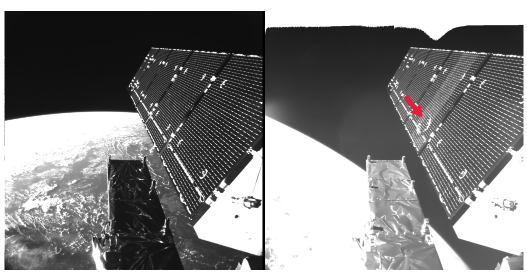
With LEO orbital objects moving at 6.9 km/s at 2,000 km altitude up to 7.8 km/s (28,080 km/hr or 17,448 mph) at 300 km altitude, even a 1 mm spec of debris can cause severe impact without the proper shielding. The European Space Agency has

several documented cases of hyper-velocity impacts from tiny debris collisions and their impacts on spacecraft.

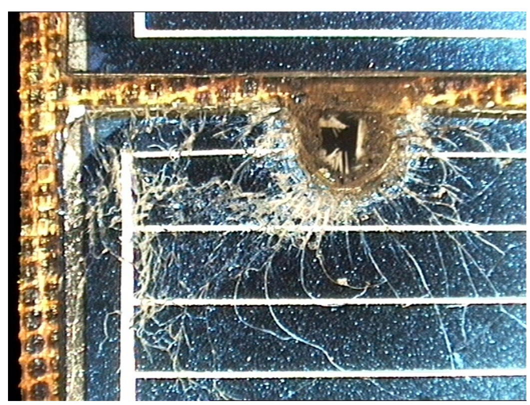
Figure 1a, taken from `https://www.esa.int`, shows the

> [Copernicus satellite] Sentinel-1A's solar array before and after the impact of a millimetre-size particle on the second panel. The damaged area has a diameter of about 40 cm, which is consistent on this structure with the impact of a fragment of less than 5 millimetres in size.

Figure 1b shows debris impacts to a solar panel taken from the Hubble Space Telescope (HST) in 2002. The HST maintains an altitude at about 540 km within the LEO regime with plenty of orbital debris. Fortunately for the follow-on mission to HST, the James Webb Space Telescope (JWST) is slated to orbit the L2 Lagrange point, 1.5 million km behind the Earth opposite the sun, far away from the majority of debris located in Earth's orbital regimes.



(a) Sentinel-1 impacts



(b) Hubble impacts

Figure 1. Debris Impacts

1.3 Potential Solutions

There already exist a number of proposed ideas and methods for managing orbital congestion with the priorities of space safety, Space Traffic Management (STM), and

Space Domain Awareness (SDA) (Schonberg, 1999). Satellite shielding helps prevent damage from particles less than 1 cm, which currently cannot be tracked by ground sensors. However, damage still occurs to unprotected solar arrays, and these shields cannot protect against larger objects which require collision avoidance maneuvering (Mespoulet et al., 2017). Conjunction analyses are used to determine whether a collision avoidance maneuver is necessary. These analyses include probability of collision as a measure of risk. Some space safety ideas include directly and indirectly removing space debris, while other ideas propose policies to implement across the international space community. Section 2.3.1 discusses these ideas in more depth. These collective ideas might solve some of the stated congestion problems. However, since space is a dynamic, competitive, warfighting domain, the United States needs to be prepared to deal with rapidly increased orbital congestion on the chance that something unpredictable happens. Thus, this thesis seeks to further decision makers' awareness and incorporation of orbital congestion into all phases of their mission design process, should it be forced upon them.

1.4 Methodology

The methodology used in this thesis improves the process of orbit selection by incorporating a value framework and introducing measures for space congestion within the orbit evaluation process. Orbits are scored based on attributes and weights input by the decision maker.

This thesis provides an illustrative example of how to measure orbits for their congestion scores and how to factor these scores into a value hierarchy including orbit mission scores. This hierarchy is then used to determine the orbit or notional orbit candidates which provides the best overall value to the decision maker to balance mission requirements and congestion when the consideration of congestion increases.

This thesis considers how orbital congestion will increase. While this thesis is by no means fully comprehensive of all problems, it does examine some of the current congestion problems and how they affect satellite mission operations. This thesis does not recommend any particular single solution, but instead proposes a broad methodological framework to build a value structure that can be fit to the needs of a given mission. This approach allows an operator or analyst to use their specific mission and orbit set to build a value structure in which they can evaluate their set of orbits as alternatives to decide where they can gain the most value for their spacecraft's mission.

1.5 Thesis Structure

The remainder of this thesis is organized as follows: Chapter 2 reviews the literature of orbit selection, how space congestion is currently considered in mission design, and introduces terms and concepts used in Chapter 3 for calculating orbital value. Chapter 3 explains a methodology used to demonstrate a decision maker's potential parameter trade-offs for mission design in a more congested space environment. Chapter 4 presents a notional demonstration of the methodology presented in Chapter 3. The results of this methodology show the most preferred orbit choices given a notional set of orbits which meet the same minimum mission requirements but provide various mission values within a decision trade-off space. The "best" candidate orbit may be altered based on this newly defined congestion factor. Chapter 5 discusses further insights from the notional demonstration and proposes potential avenues for future research. Appendix 5.4 lists the VBA code script used to automate iterative webpage data scraping and Appendix 5.4 is an Excel table showing some features of different orbital altitudes, such as speed and period, based on orbital mechanics.

II. Literature Review

2.1 Overview

This chapter reviews past research and literature dealing with orbit selection, orbital congestion, and value framework definitions.

2.1.1 Research Questions Investigated

This chapter provides background on some foundational questions like:

1. How has orbit selection been previously performed?
2. How have orbits been evaluated for selection?
3. What makes a "good" orbit?
4. Has congestion been considered in previous evaluation?
5. What is the definition of a near-miss on orbit?

An orbit's value is historically based on how well it meets mission performance needs. As of this research, it is unclear whether orbital congestion has previously been directly considered as a factor in orbit evaluation. Some works, such as sections 7.5 and 12.3 in *Space Mission Engineering: The New SMAD* (Wertz et al., 2011), reference orbital space debris, but do not mention including it as a factor in orbit selection or the orbit evaluation process. It is possible that orbital congestion has been indirectly considered within spacecraft requirements, via measures of spacecraft maneuverability and minimum fuel reserves required. It is also possible that congestion has been considered outside of orbit evaluation but still within the orbit selection process via a separate step of risk analysis. Certain orbits considered more congested than a maximum requirement threshold could be removed from the

set of orbits considered in orbit selection. For example, section 3.3.12 (page 41) in the FAA's Recommended Practices for Human Space Flight Occupant Safety recommends, "Before maneuvering to a new orbit, an operator should have the orbit screened to ensure the probability of collision with any known orbital object does not exceed 1E-4" (Administration, 2014). Congestion in this manner has been referred to as probability of collision. Probability of collision factors into risk, which is generally defined as some combination of likelihood and consequence (or impact) where higher likelihood and more severe consequence indicate higher risk (Kaplan and Garrick, 1981). The likelihood piece of orbital collision risk is generally stated as probability of collision, but different literature defines probability of collision differently. Adding to the confusion is the non-standardized consequence piece of orbital collision risk, which may be subjectively defined by specific mission consequence or in broader terms as consequence to other space objects. Section 6.3 (page 31) and Appendix O (page 143) of NASA's *Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook* give more detail on defining conjunction analysis risk assessment and collision consequences (Krage, 2020).

2.1.2 Thesis Purpose

This thesis intends to redefine orbit value from the traditional mission factors only to include measuring congestion as a factor in orbit selection.

2.2 Orbit Selection

Some missions in LEO include imagery, *e.g.*, NASA's Landsat, and internet, *e.g.*, SpaceX's StarLink. This section will provide some detail into what makes a "good" orbit selection based on objectives of these example imagery and internet missions.

Chapter 10 of Space Mission Engineering: The New SMAD (Wertz et al., 2011)

provides a detailed process for selecting an orbit in mission engineering. Table 10-1 on page 236 of Wertz et al. (2011) lists the 6 steps in the single satellite orbit selection process:

1. Establish Orbit Type(s)
2. Determine Orbit-Related Mission Requirements
3. Evaluate Orbit Performance
4. Evaluate Orbit Cost
5. Document Selection Criteria, Key Orbit Trades, Selected Orbit Parameters, and Allowed Ranges
6. Iterate as Needed

This thesis focuses on steps 2 and 3 of this process. LEO is a highly sought orbital regime due to its relatively low cost of access and high variety of missions supported. As such, this study focuses on the LEO regime for its orbit type in step 1. Mission success can be defined and measured by various factors depending on mission objectives. Step 2 of the orbit selection process is detailed in Tables 10-11 (page 258) and 10-27 (page 276) of the Wertz et al. (2011) text that list the "principal mission requirements that normally affect Earth-reference orbit design". Sections 2.2.1 through 2.2.5 of this thesis provide examples of how a few of these requirements might be viewed as mission objectives, to include maximizing overall coverage, maximizing resolution or exposure, and minimizing latency or revisit rates. In Chapter 3, this thesis proposes a methodology for step 3 to include congestion in evaluating orbital performance.

2.2.1 Coverage

If the objective were to cover the entire Earth surface area, mission success might be defined as how much total surface area of the Earth the constellation would eventually view. Mission success could then be primarily measured as a function of inclination or latitude, where higher latitudes provide more mission success.

2.2.2 Resolution

If the objective were to maximize resolution, mission success could be defined as how well a single pass's image can be interpreted, or how much detail can be seen in a small area. Measuring resolution is a function of altitude, payload equipment such as aperture and swath width, and on individual passes, weather conditions. In general, lower altitudes provide higher resolution. Figure 2 is Figure 10-14 (page 249) and 13-1 (page 359) from Wertz et al. (2011), which depicts how altitude affects imaging resolution (smaller is better) given 4 different aperture sizes. Nadir is the direction the satellite points toward the center of the Earth, the ground point directly below the satellite. A spreadsheet calculator for resolution vs. altitude at different wavelengths (Figure 2) is available as Figure 10-14 at the website `http://www.sme-smad.com`.

2.2.3 Exposure

If the objective were to maximize exposure, mission success could be measured by how much information can be captured during a single pass. Exposure can be defined by how much of a target location is visible with each pass, combined with the window of time over that location of interest. This is measured as a function of altitude or period, where higher altitudes or longer periods give potentially more time over a location of interest and more area visible each pass. This is also the case for Highly Elliptical Orbits (HEO) such as in Tundra or Molniya orbits.

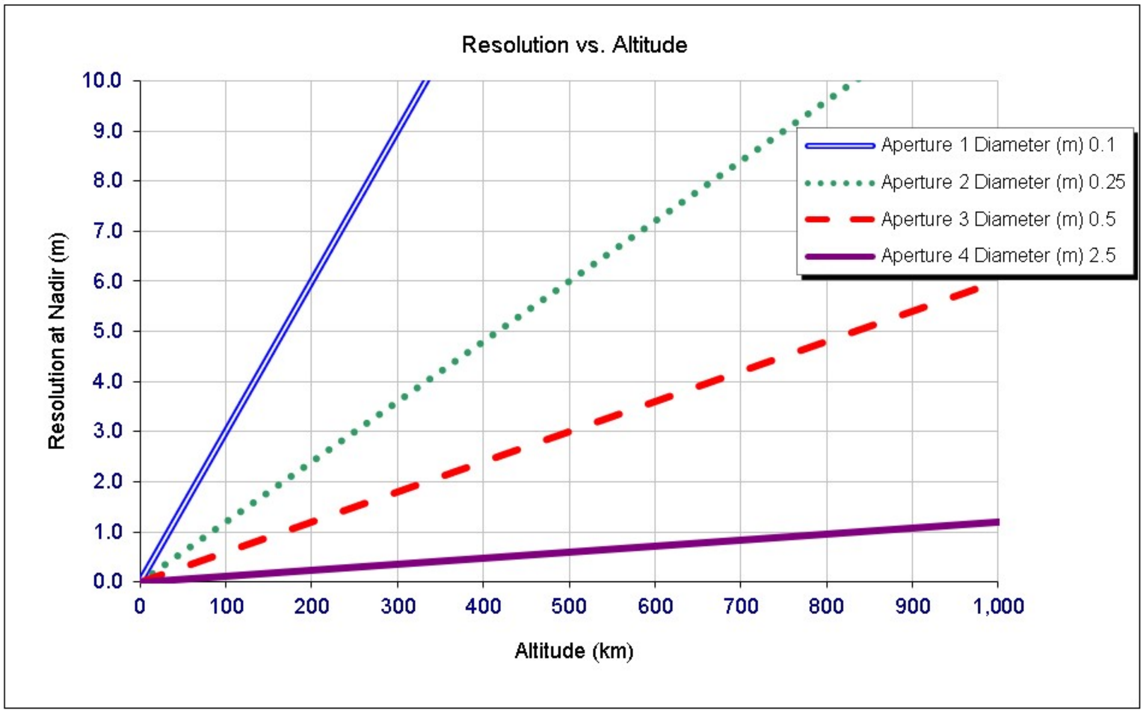


Figure 2. SME/SMAD Figure 10-14 (page 249):
Nadir Resolutions at Various Altitudes Given Aperture Size

2.2.4 Latency

If the objective were to minimize latency, mission success could be defined as how fast information can be relayed. Since information travels at a constant speed, the time it takes for information to travel is directly proportional to the distance. Thus, the objective of minimizing latency could be directly measured by minimizing distance. Orbital distance between points is primarily a function of orbital altitude. Lower altitude means less distance between points and thus lower latency, a faster signal.

2.2.5 Revisit Rate

If the objective were to minimize revisit rate between passes, mission success could be defined by how often a site is seen compared to mission need. Measuring revisit rate is a function of altitude or period, where lower altitude, and thus shorter period,

means faster passes. This translates into how often a site of interest can be updated with new information.

2.2.6 Imagery Missions

Imagery missions may have various primary and alternate objectives. For example, one imagery mission may want to map the entire globe every few years while another may be focused on collecting daily views of specific areas to show changes over time. Imagery can be performed through a variety of the electromagnetic spectrum. Some mediums for imagery include optical (visible light), infrared (IR), and synthetic aperture radar (SAR).

2.2.7 Internet Missions

Internet missions tend to be commercially focused on reaching the most amount of paying customers and providing the best service to incentivize more customers into using their service. SpaceX's StarLink, for example, aims to provide high speed, low latency internet service to remote parts of the world such as the open oceans and Africa without traditional hardwired connections. Internet mission success can be categorized by available range, speed, bandwidth, and consistency. Range can be measured by the number of potential paying customers that their service could reach. Speed can be measured by the minimum latency their service could provide. Bandwidth can be measured by available utilization and latency. Utilization is how much of the day service is available while latency is the lag between send and receive of data. Low latency is especially important for synchronous activities such as live video feed and stock exchanges.

While this section has presented several simple illustrative measures for some common mission elements, different requirements and various measures would need

to be determined by the mission to be evaluated.

2.2.8 Mission Value Improvement

Mission value for a constellation of on-orbit satellites can be improved by adding more satellites in the same orbit with different locations along same orbital path, or by adding more satellites in different orbits. These additional different orbits could be a change in plane via inclination (tilt) or RAAN (twist), or a change in period via altitude (size) or eccentricity (shape). Prior to launch, a new satellite's mission value can be improved by updating its physical capabilities through advances in technology. On-orbit Servicing (OOS), Assembly, and Manufacturing (OSAM) are upcoming capabilities that could offer increased mission life to old satellites on orbit, thus increasing mission value. Reference Luu (2021) and Duke (2021) for more details on OOS and OSAM.

For simplicity in illustrating the framework presented in this study, this thesis focuses on a single new satellite with fixed physical capabilities, along a single orbital path, without considering future orbital changes, or OOS/OSAM capabilities.

2.3 Considerations of Orbital Congestion

Several U.S. policies and doctrines including the National Security Space Strategy (NSS 2011), Defense Space Strategy (2020) and JP 3-14 (2020) have described space as a congested, contested, competitive, and/or complex environment. Space is congested due to the increase in number of objects occupying neighboring orbits. Space is contested due to internationally shared orbits which do not have clearly defined recognition of individual ownership. Space is competitive due to multiple entities holding many mission requirements among the same orbital regimes. Space is complex in the dynamic variables of orbital mechanics among the various expanding

intents and goals of countries, companies, and organizations with orbital interests. It is the responsibility of the U.S. military to defend our nation's and allies' assets, both military and civilian, anywhere they exist, including in space. The primary problem with orbital congestion is the risk of collision between active spacecraft and other orbiting objects.

2.3.1 Previously Proposed Solutions for Orbital Debris Mitigation

Several direct and indirect solutions to orbital congestion have been proposed in previous literature. Some examples of direct cleanup include collection via space robots, harpoons, and nets (Pultarova, 2018), or physically moving objects to deorbit them sooner than their natural decay rate (Tewari, 2013). According to SpaceNews, in late January 2022, China docked with and moved a defunct Beidou satellite in Geosynchronous Earth Orbit (GEO) out to a graveyard orbit (Jones, 2022). Some examples of indirect congestion prevention are found in policy proposals by agencies such as Space Policy Directive (SPD) 3 (Trump, 2018; Liou, 2018), the US Government's (USG) Orbital Debris Mitigation Standard Practices (ODMSP) (Liou, 2020), the European Space Agency (ESA), the Inter-Agency Space Debris Coordination Committee (IADC) (Committee et al., 2020), the United Nations Office for Outer Space Affairs (UNOOSA), and the International Standards Organization (ISO) (Stokes et al., 2020). These agencies require orbital debris mitigation measures to include minimizing debris released during launch and normal operations (ODMSP objective 1; IADC section 5.1), minimizing potential for on-orbit breakups (ODMSP objective 2; IADC section 5.2), and requirements for reentry risk assessments. ODMSP objective 4 and IADC section 5.3 discuss the post-mission disposal of space structures, including end of mission life atmospheric reentry from LEO or maneuver to a disposal or graveyard storage orbit for GEO spacecraft to minimize impact on future space operations

(Liou, 2020; Yakovlev, 2005).

Adilov et al. (2020) explored economic forces involved in orbital debris generation, accumulation, mitigation, and remediation. They compared debris accumulation impacts of voluntary compliance with debris mitigation guidelines to mandating a debris tax policy.

The way forward to solve the problem of space congestion depends on numerous factors such as politics, cost, and feasibility. Since most of these factors are dynamic, interdependent, and sometimes unpredictable, this thesis does not focus on any specific solution previously proposed. It instead proposes a generalized framework to evaluate alternatives to any particular mission within the scope of the broader problem of orbit selection whilst considering orbital congestion. Chapter 3 will describe how this framework was developed and Chapter 4 will demonstrate its use given notional scenario and measures by applying it to congestion factors within orbit selection.

2.3.2 Defining, Measuring, and Comparing Space Congestion

Congestion can be defined by a considered volume having a high density of objects. Orbital congestion can be defined by finding the total number of objects in a considered space divided by the total volume of considered space available. This definition gives an average answer for the total space considered, so it is more useful to consider smaller spaces. The largest useful space considered would be a range of orbits within a similar orbital regime, *e.g.*, LEO or GEO. The smallest space considered would be a single orbit and its perturbations over time.

Changes in density can be tracked by comparing how many objects' orbits are expected to intersect over a period of time. Alfano and Oltrogge (2014) provides a means of measuring congestion in space using the metric of encounters a spacecraft

will have over a period of time. This article also calculates the number of encounters expected over time at a given distance for a given orbit. This number of encounters can be used as a metric to compare congestion of different orbits. COMPSOC developed a tool, NEAT, to calculate this metric.

2.3.3 Number of Encounters Assessment Tool (NEAT)

The main measure for congestion in this thesis utilized the outputs of COMSPOC's interactive web-based tool, the Number of Encounters Assessment Tool (NEAT). NEAT is a planning and characterization tool to estimate satellite encounter rates for a prospective orbit regime. According to its website article by Oltrogge (2020),

> The Number of Encounters Assessment Tool (NEAT) is a fast, probability-based algorithm that assesses the long-term encounter rate between all pairs of satellites. Here, the term "encounter" denotes any kind of close approach event. [The user] can make the encounter represent a hard-body collision, a maneuver, or a warning by specifying the miss distance of interest.

NEAT is a tool created by Alfano and Oltrogge to calculate volumetric assessment of satellite encounter rates, which provides estimates for LEO constellation average occurrences of collisions, warnings, and maneuvers (Alfano and Oltrogge, 2018). NEAT's publicly available tool is used in this thesis to measure congestion of each orbit considered by estimating the number of encounters expected for satellite collisions, maneuvers, and warnings. More information about NEAT can be found at `https://comspoc.com/neat/` or in Alfano and Oltrogge (2015), Oltrogge et al. (2018), and Alfano et al. (2020).

Note that any tool or model that forecasts conjunctions in space can be used to measure congestion. NEAT was chosen due to its ease of use and open source availability for the demonstration in this thesis.

2.3.4 Altitude & Inclination as General Factors to Orbital Congestion

This section provides background into how orbital altitude and inclination generally trend with congestion. More missions in similar "good orbits" often lead to more congestion in those orbits due to their common functionality.

Altitude Congestion by Function and Physics

Lower altitude orbits are more congested due to function. Lower altitude is better for both imagery and internet missions, as less distance between a satellite and a ground point means less signal attenuation and lower latency between send and receive communications. Lower altitude orbits take less energy (making them less expensive) to insert or place a spacecraft in orbit. According to SpaceFlight Now, (Clark, 2016), a Falcon 9 launch to GEO Transfer Orbit (GTO) cost approximately $8,000 per kg payload, whereas a Falcon 9 launch to LEO only cost about $2,700 per kg payload. When the total weight of satellite megaconstellations can be in the hundreds of thousands of kilograms, those launch costs can be severely limiting with respect to altitude.

Lower altitude orbits are more congested, i.e., more tightly packed, due to physics. Natural orbital decay due to gravity and atmospheric drag over time brings orbits tighter, i.e., lower altitude. In addition, smaller sized orbits have less space (volume) than larger sized orbits. Given an Earth radius of 6,370 km plus altitude, and assuming the standard circle circumference equation of $C = \pi * 2 * r$, a single orbit at 300 km altitude has a circumference of approximately 42,000 km (41,909 km), whereas a single orbit at 2,000 km altitude has a circumference of approximately 52,000 km (52,590 km). A one thousand satellite constellation equally spaced in these two orbits would be approximately 10 km (12.566 km) closer to each other in the 300 km altitude orbit compared to the 2,000 km altitude orbit. These two orbits are just

the low and high altitude ranges of LEO. Equally spaced constellations in MEO and GEO get more spaced out as altitude increases. See Appendix 5.4 for further detail of these calculations.

Inclination Congestion by Function and Physics

Higher inclination orbits (up to 90 degrees) are more congested due to their function: higher inclination allows for higher latitude coverage of a satellite. Inclination of an orbit limits the maximum latitude visible to a satellite. Higher inclination orbits are more congested due to physics. Polar orbits (90 degrees inclination) have more intersections across all twists, or RAAN (defined in section 3.2.4).

Retrograde orbits, inclinations of 90-180 degrees, may be considered based on available space launch sites whose range launch westward. However, retrograde orbits are rarely considered for missions due to their going against the flow of most space objects. A spacecraft on a retrograde orbit is akin to a car driving into oncoming highway traffic, but instead of opposing at 70 mph, speeds exceed 17,000 mph. An approximate comparison in metric units is 31 m/s on the highway versus 7,600 m/s on orbit. If a direct head-on collision were to occur, impact velocity is doubled as both objects are moving opposite each other. Basic physics defines kinetic energy as mass times velocity squared. If each object were a 1 gram mass, the comparison of energy would be 0.961 Joules on the highway to 57,760 Joules on orbit, a magnitude of approximately 60 thousand times greater. The effect of a collision on orbit is exponentially greater in magnitude than one on land due to the speeds necessary to maintain natural orbit.

Orbital inclination is described in more detail in paragraph 3.2.3.

2.4 Value Focused Thinking as a Value Attribution Method

Value Focused Thinking, or VFT, is a method in decision analysis for evaluating, and potentially improving, alternatives by measuring attributes for how much value they add to the decision maker's objectives (Keeney, 1992). Keeney maintains that one should consider what is *valued* in a decision and then measure choices, i.e., "alternatives", against those values as opposed to just selecting from the alternatives that may not meet all of one's initial values. The terms value structure, value framework, value hierarchy, and value model are relatively synonymous in this thesis, but some distinctions may exist. Value structure or value framework are the most generic terms which refers to any structure or framework used to associate qualitative or quantitative value to a set of objectives or tasks. Value hierarchy refers to the generic qualitative association between objectives and their respective attributes and measures. Value model is typically the term used when value functions and weights are assigned to measures, attributes, and objectives to quantitatively attribute value to specific alternatives when evaluated through the model. This thesis incorporates a value model to frame what is important in orbit selection in order to quantitatively evaluate a set of orbits as alternatives and attribute value to them based on defined objectives and attributes. A generic value model with three objectives and two attributes per objective is given in Figure 3. The next few paragraphs define terms for value models used throughout this thesis.

2.4.1 Steps to Build a Value Structure

Adapted from Keeney (1992), the main steps in building any value model are:

1. Define Fundamental Objective

2. Define Means and Ends Objectives

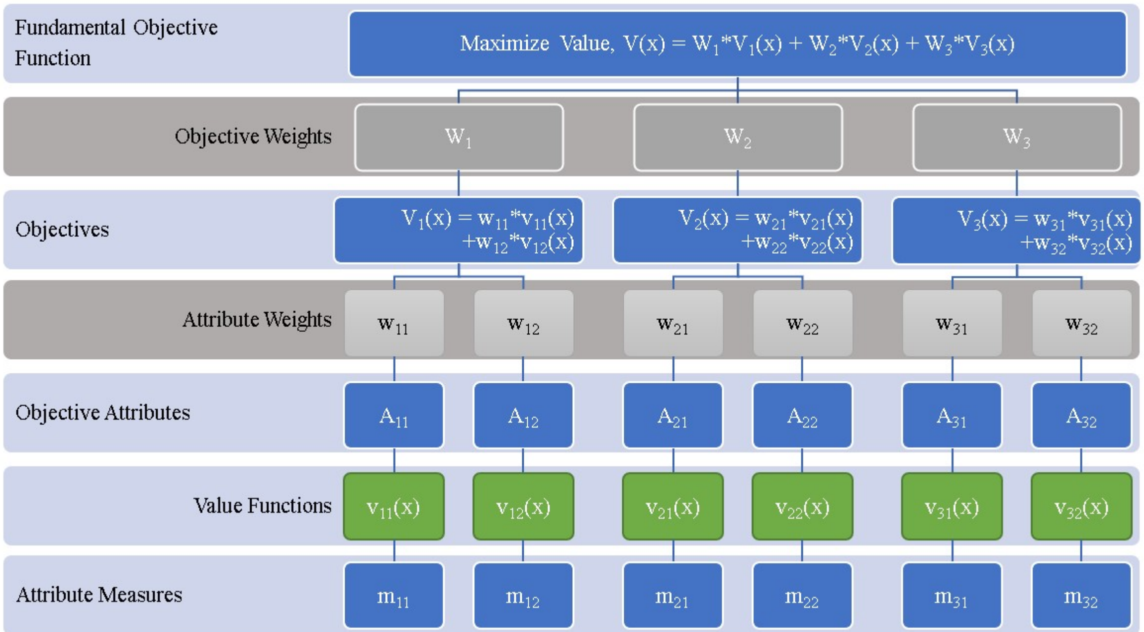


Figure 3. Generic Value Model

3. Define Attributes

4. Define Single Dimensional Value Measures

5. Define Value Functions for each Measure

6. Define Weights at each layer

2.4.2 Defining Objective(s)

As Keeney (1999) posits, "[t]he fact is that no quantitative model can be developed or used without a qualitative foundation that describes what is important to include in the quantitative model."

A value structure starts from the top-down by first defining the fundamental objective(s) using Value Focused Thinking (VFT) techniques from Ralph Keeney (1992) as follows. Fundamental Objectives are found by making a list of objectives and classifying them as means objectives and ends objectives. If an objective is

important because of its implications for some other objective, it is a means objective. If an objective is one of the essential reasons for interest in the situation, it is an ends objective and thus a candidate for the fundamental objective. The fundamental or overall objective is the primary goal of the entire decision process. Military terms may describe objectives and sub-objectives as tasks or sub-tasks (Parnell et al., 1998).

Some examples of objectives include "Minimize Congestion," "Maximize Resolution," and "Maximize Mission Success." In this set of objectives, the first two objectives are means objectives that flow into meeting the ends objective to maximize mission success. In this case, the ends objective is the fundamental objective.

This thesis focuses on a value model with a single fundamental objective, however expanding the orbit selection value model to the full extent of mission engineering may require multi-objective decision analysis techniques such as those described by Keeney et al. (1993).

2.4.3 Defining Attributes

Each objective has a set of attributes that define success for that objective. Other terms used to describe attributes may be sub-objectives, sub-tasks, or qualities (Parnell et al., 1998; Jackson Jr et al., 1996). Means objectives defined in the previous step might be used for insight to develop attributes. Some examples for attributes under an objective of "Maximize Mission Value" may include "Maximize revisit rate," "Minimize latency," or "Maximize resolution." Once objectives and attributes are defined for a given system, it can be assumed the user has a value hierarchy.

It should be noted that this thesis defines attributes and measures as separate layers, whereas in chapter 4 of VFT (Keeney, 1992), Keeney's definition of attributes are equivalent to "measures of effectiveness, measures of performance, or criterion." The next paragraph defines how measures in this thesis are a different layer than

attributes as Keeney defines them.

2.4.4 Defining Measures

Each attribute requires at least one specific measure that quantifies how alternatives will be quantitatively evaluated on that attribute. It is important that measures be single dimensional to prevent overlap of interdependent attribute features. If an attribute can be measured along a single dimension, it is a single dimensional attribute. Figures in this thesis feature only single dimensional attributes, but some attributes may require multiple measures to evaluate alternatives along the attributes' multiple dimensions. In chapter 4 of VFT (Keeney, 1992), Keeney mentions a trichotomy of attribute types: natural, constructed, or proxy. This thesis uses these types, defined the same way, to describe measures. Natural measures are directly associated with what is being measured, such as the measure "Number of collisions" to measure the attribute "Minimize Collisions" for the objective "Minimize Orbit Congestion". Constructed measures are typically used for more qualitative than quantitative objectives, and usually include categorical levels to measure value added. This thesis does not use any constructed measures, but an example of a constructed measure might subjectively score how well a satellite improves the brand of a company. Table 4.1 in VFT Keeney (1992) provides an example of how to define measure levels of a constructed attribute. Proxy measures are indirect measures used when natural or constructed measures cannot be applied to evaluate an objective's attribute.

2.4.5 Defining Alternatives

At the bottom of any value structure are the scoped set of alternatives included in the decision space. In this thesis, the decision space consists of circular orbits in LEO as its set of alternatives to evaluate in the scope of orbit selection. It is important to

properly scope the decision space and scale the set of alternatives, as this determines how many alternatives will be evaluated within the value model.

2.4.6 Defining Value Functions

Each decision maker has different definitions of value, and it is subjective to measure said value on arbitrary scales. Value functions provide a standardized way to evaluate how much value each alternative provides on each single dimensional measure of an attribute toward an objective. Value functions take an alternative's attribute measures as input and outputs the level of attribute value provided by that alternative. Value outputs in this thesis are on a scale of 0 (no value) to 1 (ideal value) in order to standardize value meaning and measure throughout the value model. Some examples of value function types are linear, exponential, piecewise, or S-shaped. Value functions can provide continuous scores from 0 to 1, or specified categorical scores such as 0, 0.25, 0.5, 0.75, or 1.

For any alternative x, the overall value function for the fundamental objective is shown in Figure 3 as capital $V(x)$ with no subscripts. Objective value functions are shown as capital $V(x)$ with single subscripts representing which objective they score. Value functions for each measure m are shown as lower case $v(x)$ with subscripts corresponding to the respective objective and attribute A being scored. If multiple measures were required to score a multi-dimensional attribute A, a third subscript would be required on each measure m and value function $v(x)$.

2.4.7 Assigning Weights

Once each measure has a value function developed and assigned, the scoring structure is finalized by assigning weights to determine relative importance at each layer. Attribute weights define relatively how important each attribute is to its objective

compared to other attributes under that objective. Objective weights define how important each objective is relative to other objectives. Attribute weights are denoted here by lowercase w with subscripts corresponding to the respective objective and attribute A it is assigned. Objective weights are denoted here by uppercase W with subscript corresponding to its respective objective.

2.4.8 Scoring and Evaluating Alternatives

Before evaluating every possible alternative, it may be desirable to scope the decision space to a sample range to assess the validity of the value model. Evaluating a few alternatives at known extremes for each attribute's value range can help validate value functions and weight assignments. Each alternative selected is evaluated through the value structure for an overall value score, and all alternatives scored are compared for relative value to the fundamental objective.

2.5 Summary

This chapter reviewed past research and literature dealing with orbit selection, orbital congestion, and value attribution methods.

III. Model Methodology

3.1 Overview

This Chapter explains a generalized methodology that can be used to determine a satellite orbit's value. It starts with a brief overview of orbital mechanics to summarize how orbits are defined. It then lists the steps used in building the value structure and expands upon each step with techniques used.

3.2 Orbital Mechanics Review

Earth orbits are traditionally defined by Keplerian elements, or classical orbital elements (COEs). The COEs in generalized names are orbital size, shape, and plane. The orbital plane is defined via tilt, twist, and elliptical orientation. More specifically, orbital elements are defined by Altitude (size), Eccentricity (shape), Inclination (tilt), Right Ascension to the Ascending Node - RAAN (twist), and Argument of Perigee (elliptical orientation/rotation). A specific spacecraft's location within an orbit is given by true anomaly. In the following paragraphs are definitions of these COEs summarized from Chapter 5 of *Understanding Space: An Introduction to Astronautics* (Sellers et al., 2005) and Section 9.1.5 (page 202) of Wertz et al. (2011) and which COEs apply in this thesis.

3.2.1 Size - Altitude

Orbital size is defined by its semi-major axis, or half the distance of the longest chord of the orbital ellipse. In a circular geocentric orbit, its semi-major axis is simply the radius of the circle that traces the orbit. In other words, a circular orbit's semi-major axis is the distance from the center of the Earth to any point on the orbit. This thesis utilizes orbital altitude as a primary definition for an orbit. Orbital altitude

is defined as the distance above Earth's surface, measured in kilometers (km). To convert from semi-major axis to altitude in a circular orbit, one simply subtracts the radius of the Earth, i.e., 6,738 km (Williams, 2004), from the semi-major axis to get altitude. The Low Earth Orbit (LEO) regime is generally defined as altitudes between 300-2,000 km (186-1243 miles). LEO satellites make one revolution around the Earth in a period between 90-127 minutes depending on altitude. For circular orbits, higher altitude orbits have longer periods, meaning it takes longer for higher satellites to make a revolution around the Earth. The Geosynchronous Earth Orbit (GEO) regime is at 35,786 km altitude with a period of approximately 24 hours, where satellites orbit the Earth at the same rate that the Earth rotates. The Medium Earth Orbit (MEO) is by far the largest Earth orbital regime, anywhere between LEO and GEO at 2,000-35,786 km. The primary mission within MEO is at 20,350 km with a 12-hour period, where Position, Navigation, and Timing (PNT) satellites such as GPS (Global Positioning System) tend to be stationed. While the LEO regime will be the primary scope of this thesis, other more complex orbital classes are defined in Table 1.2 (page 11) of *ESA's 2021 Annual Space Environment Report* (Krag, 2021), or at `https://sdup.esoc.esa.int/discosweb/statistics/`.

3.2.2 Shape - Eccentricity

Orbital shape is defined by its eccentricity, e, in how circular or elliptical an orbit is. When $e = 0$, the orbit is a perfect circle with the center of the Earth at the center of the orbit as both foci. Highly Elliptical Orbits (HEO) are a type of orbit with an eccentricity above 0.2, such as the Tundra orbit, or as high as 0.7, such as the Molniya orbit. For purposes of illustrating the proposed approach, this thesis focuses on circular geocentric orbits in LEO, and does not expand into orbits that are eccentric ($0 < e < 1$), parabolic ($e = 1$), or hyperbolic ($e > 1$), *i.e.*, escape

orbits. Table 5-1 and Figure 5-3 on page 157 from Sellers et al. (2005) give a better understanding of eccentricity.

3.2.3 Tilt - Inclination

Orbital tilt is defined by its inclination. Inclination measures the orbital plane's tilt in degrees with respect to the equator. Inclination also defines the direction of an orbital path with respect to the rotation of the Earth. 0 degrees inclination is a perfectly prograde equatorial orbit, *i.e.*, the ground track traces the equator in the same direction of Earth's rotation. 90 degrees inclination is a polar orbit, that is, the spacecraft passes directly over both the north and south poles. 180 degrees inclination is a perfectly retrograde equatorial orbit, *i.e.*, the exact opposite direction of 0 degrees inclination. Inclination, paired with swath width, dictates the highest latitude the satellite will be able to view at any point in its orbit. Table 5-2 on page 158 from Sellers et al. (2005) shows various types of orbits defined by inclination.

3.2.4 Twist - RAAN

Orbital twist is measured by RAAN, or Right Angle of the Ascending Node, which is the longitude at which the orbit passes the equator toward the northern hemisphere. RAAN is basically the orbital twist around the north/south pole for a specific revolution. RAAN varies with respect to the orbital harmonics between a spacecraft's period compared to the Earth's rotation. As the Earth rotates underneath an orbit, the ascending node changes with every revolution. This is easiest to visualize with a ground track of an orbit. Fu et al. (2012) describe some orbital harmonics, design of repeat-groundtrack orbits, and how to understand perturbations that cause ground track drift as shown by secular change in RAAN. Orbits in the LEO regime can make 11-16 revolutions around the Earth on any given day, and depending on

orbital harmonics may take several days to cross the same equatorial longitude or ground track. Some spreadsheet calculations for orbital mechanics such as period's relationship to altitude are available in Appendix 5.4. Notable twist mechanics include sun-synchronous orbits which pass over Earth points with the same sun angle, semi-synchronous orbits which pass over the same longitude twice per day, and the GEO regime where the spacecraft is constantly over the same longitude every time it passes the equator. Figure 5-6 (page 159) in Sellers et al. (2005) describes RAAN as swivel.

3.2.5 Elliptical Rotation - Argument of Perigee

Orbital elliptical rotation, measured by argument of perigee, only applies to eccentric orbits and is undefined for circular orbits. Any given point on a circular orbit is equidistant from the center and thus could be apogee or perigee. Since the scope of this thesis includes only circular orbits, elliptical rotation is not considered as an attribute in the demonstration model.

3.2.6 Spacecraft Location - True Anomaly

Spacecraft location, measured by true anomaly, is specific to where a spacecraft is within its orbit at a given point in time, or epoch. True Anomaly is undefined for circular orbits, and since the model presented in this thesis spans over days or years, true anomaly is not considered a useful feature at this model's resolution.

3.2.7 Orbital Mechanics Summary

This section reviewed COEs of size, shape, tilt, twist, rotation, and location based on the work of Sellers et al. (2005). Table 5-3 on page 161 of Sellers et al. (2005) gives a summary of COEs. The COEs measuring orbital twist, rotation, and space-

craft location are more pertinent at higher resolution models dealing with individual satellites at specific times. Over longer time spans, these more specific COEs average out and are not used in more aggregated models such as the one presented in this thesis.

3.3 Building the Value Hierarchy

Using the terms defined in Section 2.4, this section explains how a value structure can be framed in the context of orbit selection. An illustrative example value model generalized for comparing mission and congestion objectives in orbit selection is shown in Figure 4. It is worth noting that this model may be made more complex by adding additional objectives, *i.e.*, extending the index j, or by adding additional attributes, *i.e.*, extending the index n, k, and so forth as required by a specific mission being modeled.

3.3.1 Value Equations

In value models throughout this thesis, the overall value function is calculated by summing the weighted objective values. The overall score for orbit x is calculated by equation 1, where W_j is the weight for objective j and $V_j(x)$ is the total value provided by objective j.

$$\begin{aligned} V(x) &= \sum_{\forall j}[W_j \times V_j(x)] \\ \text{such that} \sum_{\forall j} W_j &= 1 \end{aligned} \tag{1}$$

The total objective j value score of an orbit x is given by $V_j(x)$ and is calculated by equation 2, where i is the index for attributes and w_{ji} is the weight assigned to

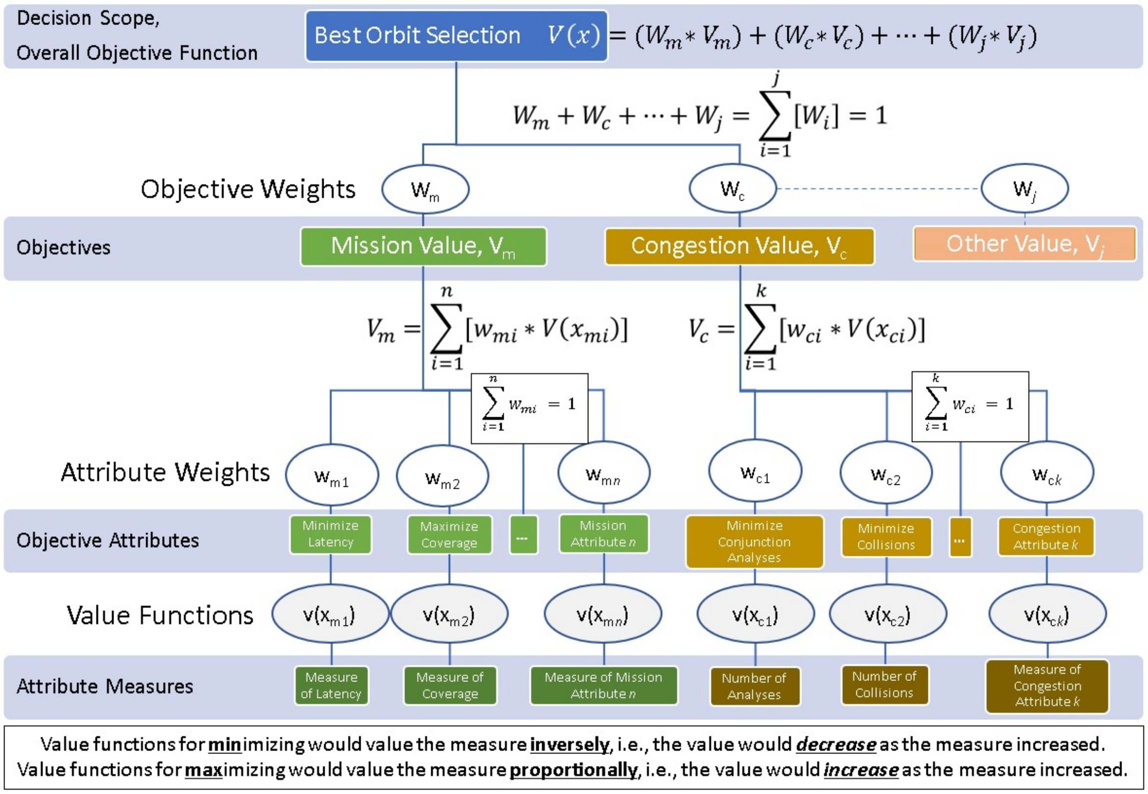


Figure 4. Generalized Orbital Value Hierarchy

attribute i under objective j.

$$V_j(x) = \sum_{\forall i}[w_{ji} \times v_{ji}(x)]$$
$$\text{such that} \sum_{\forall i} w_{ji} = 1 \text{ for each } j \tag{2}$$

3.3.2 Assigning Objectives

In the decision context of selecting the best orbit, an example fundamental objective may be to "Maximize Satellite Capability". This value hierarchy may have one objective with attributes defining mission success, *i.e.*, V_m in Figure 4, and another objective with attributes defining how much congestion exists, *i.e.*, V_c in Figure 4. While these two are used in this illustrative example, other primary objectives may exist in other scenarios and could be added into the model as an applicable V_j.

3.3.3 Assigning Attributes and Measures

Attributes and measures for each objective can be determined with any appropriate analysis or model. This thesis' demonstration value model assigned notional mission attributes and measures and used NEAT outputs to measure attributes of congestion.

All attributes used for demonstration in this thesis are considered single dimensional attributes, requiring only one single-dimensional measure to evaluate alternatives. As mentioned in 2.4.4 however, attributes may not be single dimensional in other value models. Multi-dimensional attributes require multiple single-dimension value measures, each with their own weights and value functions that feed into the attribute layer. Since the objective "Maximize Resolution" might have three primary factors of altitude, swath width, and aperture size that can be used as measures, if more than one of these are variable then this attribute is a multi-dimensional. The demonstration in this thesis assumes constant aperture size and swath width as part of altitude, thus the "Maximize Resolution" mission objective attribute is considered single-dimensional with the single measure of altitude.

3.3.4 Assigning Value Functions

Value function types may be continuous linear, piecewise linear, exponential, or an S-curve. Value functions are required to be monotonic. A single dimension value function can also be categorical, if needed to represent the attribute. One method used to provide piecewise linear functions, which can also approximate an S-curve, is to define points in a measure associated with set values. In a bisected example, these levels could be:

1. no value (score of 0)

2. lower quartile inflection point (score of 0.25)

3. midrange value (score of 0.5)

4. upper quartile inflection point (score of 0.75)

5. ideal value (score of 1)

First, the values of 0 and 1 are defined by the decision maker to mark at what point (or below that point) no value is achieved, and then at what point (or above that point) no extra value is added, respectively. Next, a mid-value point is defined by finding where in the measure provides half the ideal value. The mid-value point is verified by inversely ensuring the ideal point provides twice the value of that half-value point. This mid-value process is repeated for both the lower quartile and upper quartile, using the ranges of 0 and 0.5, and 0.5 and 1, respectively, to find those inflection points in the value function.

A categorical value function may include levels based on preference, such as from least to most preferential. Since this type of value function may have alternative based bias, it is less reliable if measures of all alternatives are not known.

3.3.5 Assigning Weights

Value functions and weights quantitatively define how single dimensional measures apply value to objectives within the model. As mentioned in 2.4.7, weights determine relative importance of an objective or attribute with respect to other objectives or attributes. Weights act as a scalar multiplier for relative importance, and as such they are restricted to sum to 1 at each layer. If all attributes for an objective are equally weighted, then the importance for each attribute of that objective is scaled by the inverse of the total number of attributes. In other words, adding more attributes of equal importance makes each individual attribute less important.

Time is the primary limiting factor when eliciting inputs from decision makers to build a value model. As such, different weighting methods offer different levels

of interaction thus trading off intricacy and time needed to develop. Trainor and Parnell (2007) compared interviews, focus groups, and surveys as means to interact with stakeholders.

Some methods for assigning weights include Parnell and Trainor's swing weight technique (Parnell and Trainor, 2009) or simply assigning percentages at each tier of the hierarchy. One version of swing weighting method was tried to determine importance of congestion factors. The list of attributes were ordered from most to least important. Next, the least important attribute was set equal to 1 unit of importance. For example, collisions were deemed more important than maneuvers and maneuvers more important than warnings, so warnings were set equal to 1 unit of importance. This provided a baseline for relative importance comparison between attributes. Next, relative importance was assigned between different attributes. For example, collisions may be deemed twice as important as maneuvers, and maneuvers may be deemed five times as important as warnings. These comparisons created a set of linear equations that were solved to define relative units of importance to each attribute. In this case since the lowest attribute of warnings had been defined at 1 importance unit, five times 1 is simply 5 units of importance for maneuvers, and two times 5 is 10 units of importance for collisions. Next, weights were assigned by scaling the importance units, or summing the total number of importance units and taking each attribute's ratio. For example, 1, 5, and 10 sum to 16, so warnings were worth 1/16th total importance, a weight of 0.0625 for w_{c1}. It follows that maneuvers were worth 5/16 scaled units of importance, a weight of 0.3125 for w_{c2}, and collisions were worth 10/16 scaled units of importance, a weight of 0.625 for w_{c3}. For other reasons described in the demonstration, this method was exchanged for a simpler weighting scheme in Chapter 4.

It is possible to have a value model that is not in a hierarchy but instead combines

all measures intricately into a single overall objective function. The value hierarchy helps to visualize flow of value as well as relative importance of various measures.

The Perduco Group has a web based tool that can be used to design a value hierarchy and assign various value functions and weights. The Perduco tool includes weighting methods of manual, rank order centroid, pairwise, and swing weights. Their tool ensures all weights at each tier sum to 1, and is useful for quickly comparing local and global weights. Figure 5 shows how the Perduco tool can handle and compare local and global weights. Local weights are the weights assigned at a specific tier showing how a measure or attribute relatively compares to its neighbors. Global weights show the overall influence a specific objective or measure has on the overall model. Comparing global weights at lower tier measures both provides insights toward factor analysis or how important any given measure is to the model, and it helps to validate or improve the model if a measure's importance is deemed too high or too low. The Perduco VFT tool is located at `http://vft.theperducogroup.com/`.

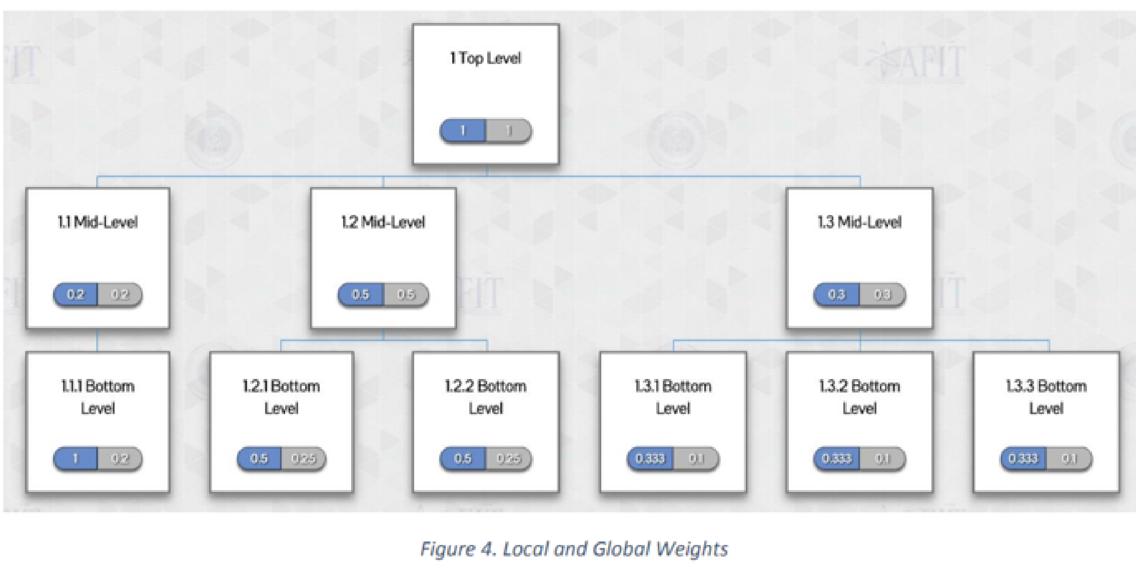


Figure 5. Perduco's VFT Global and Local Weights
`http://vft.theperducogroup.com/VFTManual.pdf`

3.4 NEAT

As introduced in Section 2.3.3, this thesis used NEAT to measure congestion for the proposed value model. This section, based on details from the NEAT webpage, summarizes inputs, outputs, and key features of NEAT used in the value model. Figure 6 shows a screenshot of the NEAT webpage (`https://comspoc.com/neat/`) from 28 January 2022 as a visual for what inputs and outputs a user can expect to find.

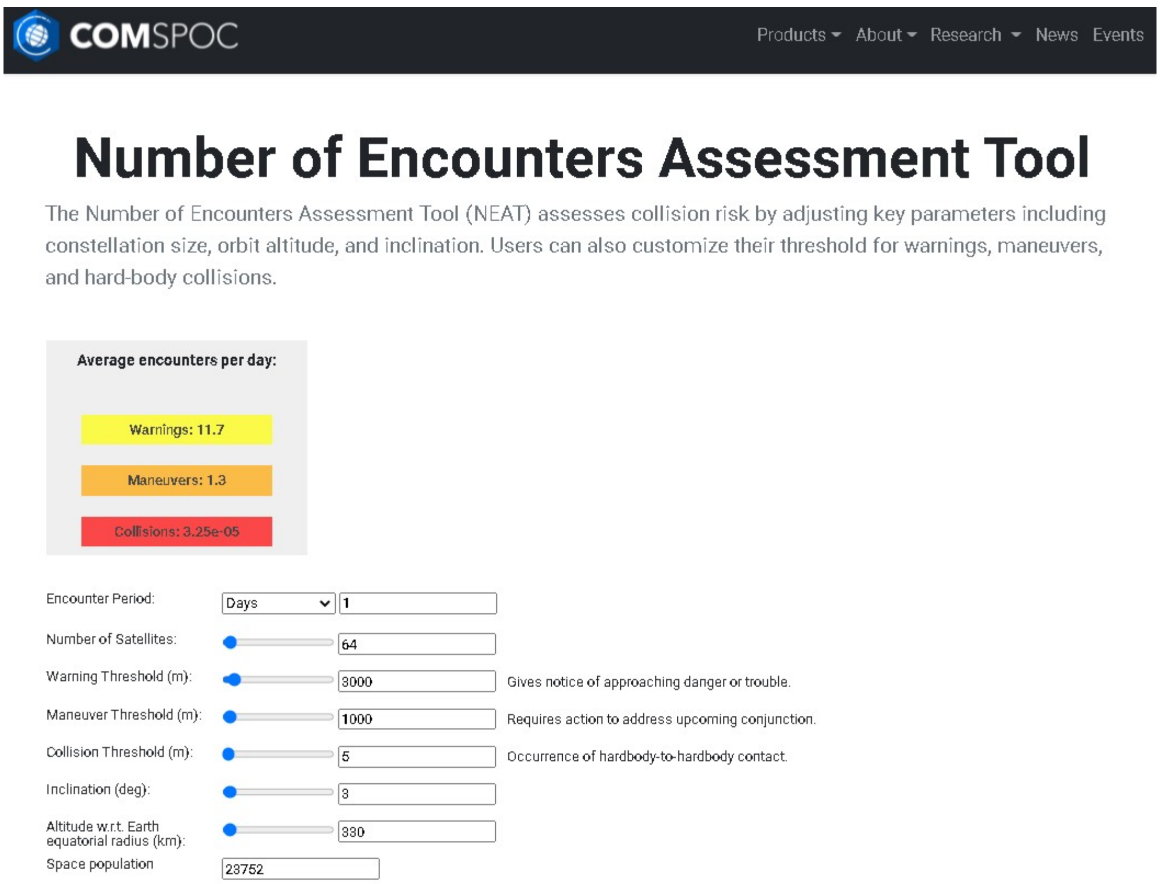


Figure 6. NEAT Website Interactive Tool (28 January 2022) https://comspoc.com/neat/

3.4.1 NEAT Inputs

The user has several degrees of freedom in which they can utilize NEAT. The user can define the:

- Time period length of interest as a whole number; in days, months, or years
- Number of satellites within the single orbit constellation
- Warning threshold: miss distance which within a Warning would occur (default is 3km)
- Maneuver threshold: miss distance within which the user considers a Maneuver to be required (default is 1km)
- Collision threshold: distance that is considered a collision. This could be the size of the spacecraft or larger to include uncertainty (default is 5 meters)
- Inclination (0-180) of the constellation orbit in degrees
- Altitude (300-2,000) of the constellation orbit in kilometers
- Space population, *i.e.*, the number of other tracked objects populating space

Note that the publicly available version of the NEAT tool limits eccentricity to 0, *i.e.*, it only assesses circular orbits based on user inputs described.

The default inputs when opening NEAT are set to 1 day, 64 satellites in the tested orbit's constellation, warning threshold at 3,000 meters, maneuver threshold at 1,000 meters, collision threshold at 5 meters, inclination at 3 degrees, altitude at 330 kilometers, and the space population 23,752 (as of 28 January 2022). It should be noted that the default space population on 12 February 2021 was 19,697; an increase of over 4,000 objects in less than a year.

3.4.2 NEAT Outputs

The three outputs taken from NEAT are the number of encounters expected at user defined miss distances. These encounter outputs are labeled “Warnings,” “Maneuvers,” and “Collisions.” Given the user defines these miss distance thresholds in descending distances at their relative risk thresholds, the user can respectively view these three outputs as how many times their spacecraft(s) will be close to, be very close to, and collide with another object in space over the user defined time period. The default inputs listed above provided default outputs of 11.7 Warnings, 1.3 Maneuvers, and 3.25e-05 Collisions as of 28 January 2022. It should be noted that as of 12 February 2021 these same inputs, with the exception of space population as noted, provided immediate encounter outputs of 1.46 Warnings, 0.162 Maneuvers, and 0 Collisions. A 20% increase in space population equated to an 8-fold increase in encounters. This change is detailed in Figure 19, which is located and discussed in Section 4.5.1.

3.4.3 Use of NEAT in this Thesis

The primary measurement for congestion used in this thesis' demonstration was the number of expected encounters as calculated by COMSPOC's NEAT, an open source web-based tool located at
`https://comspoc.com/neat/`. Details about NEAT's inputs and outputs are mentioned in Sections 3.4.1 and 3.4.2. NEAT's website provides an interactive 3D plot of a surface of points to visualize which orbits have more encounters than others. A screenshot of this surface is included as Figure 7.

Each point on this surface is a circular orbit defined by altitude and inclination. Showing the full LEO range of 300-2,000 km altitude and 0-180 degrees inclination, separated every 5 km altitude and every 5 degrees inclination, this surface contains

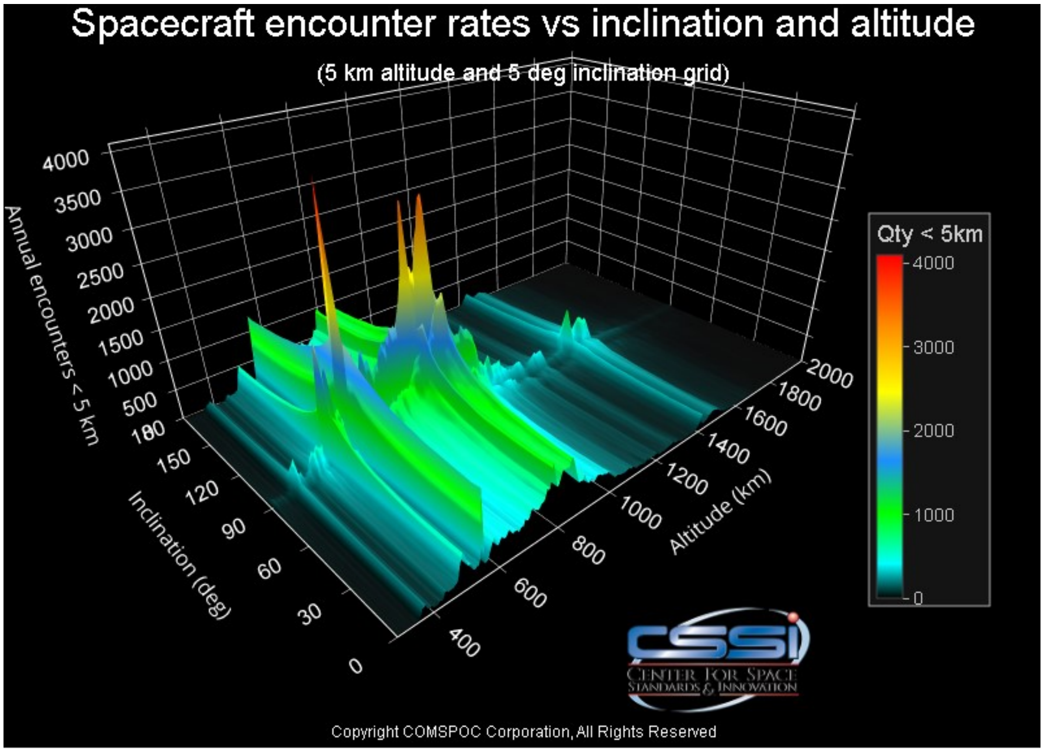


Figure 7. Interactive Surface on NEAT Website,
`https://comspoc.com/neat/`
Image provided courtesy of COMSPOC Corporation; all rights reserved.

an estimated total of 12,617 points. A higher resolution recreation of this surface was desired and explored. If varying only altitude and inclinations at increments of 1 km by 1 degree were used, holding all other variables constant, there are a total of 307,881 candidate orbits that could be measured in NEAT. Each orbit input may take five seconds to process, per the conclusion of NEAT's source article (Alfano and Oltrogge, 2018), which would take 427 hours to pull data on all orbits. Even with automated collection techniques, the set of orbits needed to be scoped in order to collect enough data in a manageable amount of time.

Table 1 shows potential orbit scopes for use as input ranges using NEAT as a congestion measure. By increasing increments of inclination and altitude from 1 to 5 each, this reduces the number of points needed to 12,617. The surface in Figure 7 appears approximately symmetrical about polar inclination, and paired with the

Table 1. Scoping Selected Set of Orbits

Description:	Inc Rng		Inc sep	Alt Range		Alt sep	Total points
NEAT's Full Range (varying only Alt/Inc)	0	180	1	300	2,000	1	307,881
Figure 7 Surface	0	180	5	300	2,000	5	12,617
Thesis Demo Range	0	90	5	300	2,000	5	6,479

assumption that retrograde orbits will soon be counterproductive to any operations in LEO, a fair assumption to make would be to only evaluate prograde, *i.e.*, 0 to 90 degrees, inclinations for use in this notional demonstration. This cuts the range of inclinations, and thus total number of orbits to be evaluated, by about half. The number of orbits to evaluate is now at 6,479 for this illustrative example.

Figure 8 is from NASA's Orbital Debris Program Office (ODPO) at Johnson Space Center (JSC), and shows the spacial densities of catalogued objects as of January 2013 to include distinction of fragments created by the 2007 Chinese ASAT test (FY-1C) and the 2009 Iridium-COSMOS collision (Stansbery, 2016). A similar chart from the same source is used as Figure 7-15 in Wertz et al. (2011) (page 139), which shows spatial densities in particles per cubic kilometer across all Earth orbits (A) and zoomed into LEO (B), as of January 2011. Where Figure 7 shows orbital congestion through number of expected encounters at each altitude and inclination, Figure 8 shows orbital congestion through the density measure using only altitude.

3.4.4 Data Collection and Scoping

With the assistance of Dr. Jeffrey Weir, a coding script was developed in Microsoft Excel's VBA environment. This script is attached in Appendix 5.4. This coded script automated the process of data collection from NEAT's website. By initiating new default inputs and iterating through altitude and inclination inputs, this code automated the capability to collect thousands of data points. This automation allowed a much wider range for data exploration of NEAT's full potential.

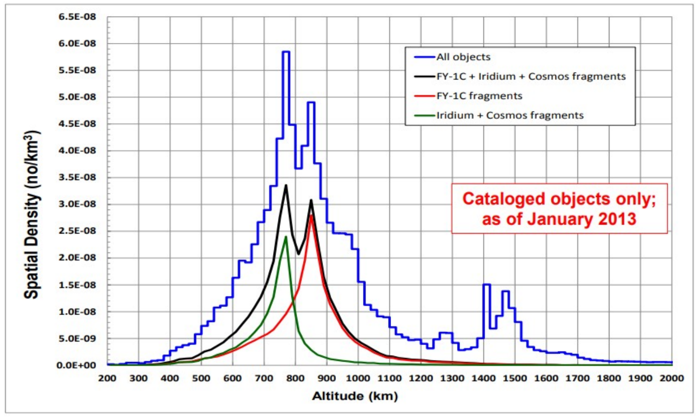


Figure 8. January 2013 Catalogued LEO Spacial Densities, Image Courtesy of NASA's Orbital Debris Program Office (ODPO)

3.5 Summary

This Chapter explained a generalized methodology that can be used to determine a satellite orbit's value. This Chapter reviewed orbital mechanics, detailed the steps used in building a value structure, and profiled NEAT as a means to collect and scope measures for congestion. Chapter 4 provides an illustrative scenario utilizing the methodology developed in this Chapter.

IV. Notional Demonstration and Analysis

4.1 Overview

Chapter 4 demonstrates a notional example of the value model techniques explained in Chapter 3 and provides insights into incorporating congestion as a part of orbit selection decision analysis.

4.2 Notional Value Model

This thesis' value model assigned notional mission measures to attributes and used NEAT outputs to measure attributes of congestion. Figure 9 presents the specific value model used in this demonstration to compare mission and congestion values via weighted attributes for each objective. The overall objective in this demonstration is to find the preferred orbit with the objectives of maximizing mission value added and minimizing congestion present for a set of orbits. From equations 1 and 2, the Objective index j consists of m for mission and c for congestion; while the attribute index i consists of 1 and 2 under mission and 1 to 3 under congestion.

While any number of meaningful objectives can be developed to measure orbital value based on mission and/or constellation requirements, only a minimum number have been used in this notional example. The purpose of this notional example is to demonstrate how the framework can be implemented and utilized when developed for and populated with an actual mission.

Notional mission factors in this demonstration included maximizing resolution and maximizing latitude coverage. Resolution was measured solely by altitude (weight and value function subscripts $m1$), where lower altitude provided better resolution. Latitude coverage was measured solely by inclination (weight and value function subscripts $m2$), where higher inclination provided more latitudinal coverage.

Congestion factors in this demonstration included minimizing conjunction analyses, maneuvers, and collisions. Conjunction analyses were measured by number of warnings (weight and value function subscripts $c1$). Maneuvers were measured by number of maneuvers (weight and value function subscripts $c2$). Collisions were measured by number of collisions (weight and value function subscripts $c3$).

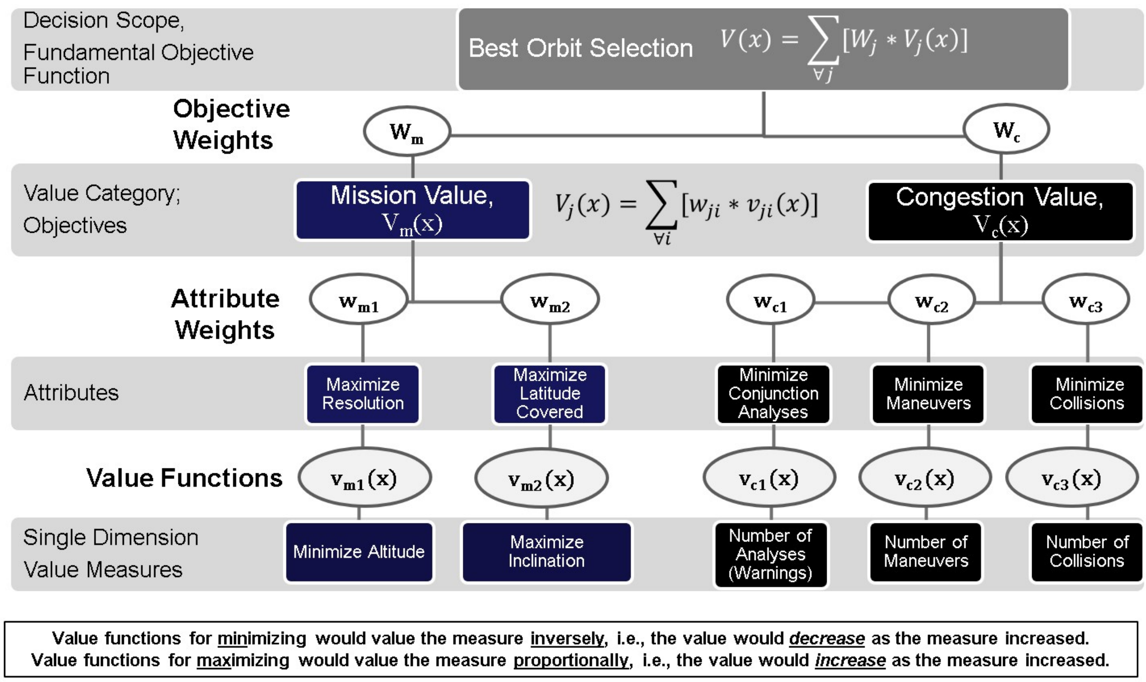


Figure 9. Value Hierarchy for Notional Demonstration

Value functions and weights for these demonstration measures will be defined in the following subsections. While only limited measures are used in this demonstration, the reader is reminded that multiple measures may be used as required by the specific mission.

4.2.1 Demonstration Value Functions

Some value function shapes can be seen in Figure 10. The top left is continuous linear. The top middle is piecewise linear. The top right is categorical. The four in the bottom left are various exponential value function curves. As the

shape in the bottom right suggests, it is an S-shaped value function curve. Details on value function graphs can be referenced in Perduco's online VFT tool Manual (`http://vft.theperducogroup.com/VFTManual.pdf`), starting on page 12. For this demonstration, only continuous linear and piecewise linear shaped value functions were used.

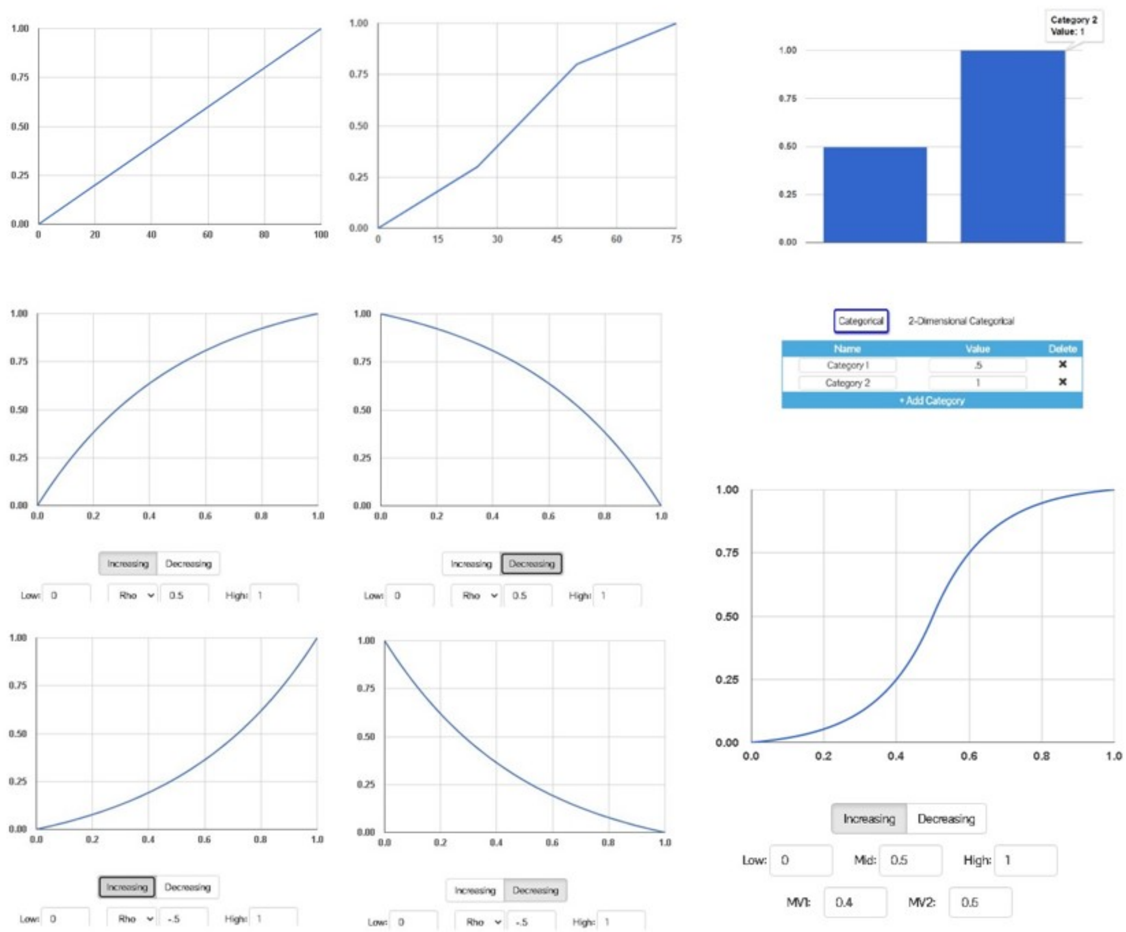


Figure 10. Value Function Shapes from Perduco's VFT tool
`http://vft.theperducogroup.com/VFTManual.pdf`

Demonstration Mission Value Functions

Since this demonstration was a notional mission example, it used linear value functions to define value provided by mission measures. The minimum and maxi-

mum ranges for altitude (300-2,000 km) and inclination (0-90 degrees) set the value extremes, and an even slope was calculated between these extremes for each measure. Note that if the scope of orbits changed such that the ranges of the altitude or inclination increased or decreased, the value function based on this method would need to be reexamined.

The value function for the maximizing resolution attribute, measured by minimizing altitude, was calculated using a continuous linear slope-intercept formula in Excel to be $v_{m1}(x) = -0.0006 * (\text{orbit's altitude in km}) + 1.17647$ such that 300 km altitude would give a value of 1 and 2,000 km altitude would give a value of 0. The negative slope indicates that lower altitude provides better value.

The value function for the maximizing coverage attribute, measured by maximizing inclination (at 90 degrees), was calculated using the same continuous linear slope-intercept method in Excel to be $v_{m2}(x) = 0.01111 * (\text{orbit's inclination in degrees}) + 0$ such that 90 degrees inclination would give a value of 1 and 0 degrees inclination would give a value of 0. The positive slope indicates higher inclination provides better value.

The value function for combined mission attributes is given as $V_m(x) = v_{m1}(x) * w_{m1} + v_{m2}(x) * w_{m2}$, where the weights will be defined in a subsequent section.

Demonstration Congestion Value Functions

The only metric found in literature that defines an anchor value for congestion is keeping probability of collision under a certain threshold. Section 3.3.12 (page 41) in the FAA's *Recommended Practices for Human Space Flight Occupant Safety* (2014) recommends, "Before maneuvering to a new orbit, an operator should have the orbit screened to ensure the probability of collision with any known orbital object does not exceed 1E-4."

By examining the interactive surface on NEAT's webpage (Figure 7), it is easy to

visually locate the orbits with the most and least number of encounters. In general, the highest number of encounters occur at polar inclinations, *i.e.*, 90 degrees inclination, while the lowest number of encounters currently occur at equatorial inclinations, *i.e.*, 0 degrees inclination. The orbit at 80 degrees inclination and 845 km altitude was determined to be the most congested with 53,403 annual warnings at 3,000 meters and 5,934 annual maneuvers at 1,000 meters. This orbit was used as an anchor point to assign value functions to measure congestion attributes.

Figure 11 shows the method used to define piecewise linear value functions for Warnings and Maneuvers as measures of congestion. The metric of encounters per day was used as a baseline to form opinions of how much value remains at certain points. Slope-intercept calculations defined the line segments between each point, and the equation outputs as a value function shape is shown in Figure 12.

Warnings (3000m)		per day	Annual # of Warnings, (x)	Value, v(x)
best	0 encounters is ideal	0	0	1.00
MV1	MV1 provides 3x value as MV2	8	2920	0.75
mid value	half value of ideal; twice value as MV2	10	3650	0.50
MV2	MV2 provides 1/3 value of MV1	24	8760	0.25
worst	any more is 0 value	48	17520	0
		max in set:	53403	0

Maneuvers (1000m)		per day estimate	exact per day	Annual # of Maneuvers, (x)	Value, v(x)
best	0 encounters is ideal	0	0	0	1
MV1	MV1 provides 3x value as MV2	0-2	1.6	584	0.75
mid value	half value of ideal; twice value as MV2	2	2	730	0.5
MV2	MV2 provides 1/3 value of MV1	2-3	2.4	876	0.25
worst	any more is 0 value	3+	3	1095	0
			max in set:	5934	0

Figure 11. Congestion Value Function Determinations

The set of piecewise value functions for the minimizing conjunction analyses attribute, measured by minimizing number of warnings, is given by $v_{c1}(x)$ and is shown

in the top chart of Figure 12.

The set of piecewise value functions for minimizing satellite maneuvers attribute, measured by minimizing number of maneuvers, is given by $v_{c2}(x)$ and is shown in the bottom chart of Figure 12.

The value function for minimizing collisions attribute, measured by minimizing number of collisions, is given by the binary function $v_{c3}(x) = 1, if x = 0; 0, if x > 0$.

The value function for combined congestion attributes is given as $V_c(x) = v_{c1}(x) * w_{c1} + v_{c2}(x) * w_{c2} + v_{c3}(x) * w_{c3}$, where the weights will be defined in a subsequent section.

4.2.2 Demonstration Weighting

Demonstration Mission Weighting

For notional mission attributes in this example scenario, resolution gained at lower altitudes was perceived equally as important as the coverage provided at higher latitudes (measured by inclination). Thus, both the altitude measure (w_{m1}) and inclination measure (w_{m2}) were weighted 0.5 each. Of course, the requirements of a specific mission would dictate the levels appropriate for an actual system.

Demonstration Congestion Weighting

In this demonstration's data collection, the amount of collisions remained at 0, even for the collection at 200,000 Resident Space Objects (RSO) space population. The collisions measure thus became erroneous, as all values scored to 1 for this measure and provided no insight to the model. This was assessed as an artifact of the data collection among the 6,000+ points twice. To provide a reasonable simple adjustment, the weight assigned to collision measure was set to zero, and the weights of Warnings and Maneuvers were initially split equally at 0.5 each. Thus, $w_{c1} = w_{c2} = 0.5$ and

$w_{c3} = 0$. Since closer encounters incur more risk to satellites, a more realistic weighting scheme was instantiated between the two measures. The measure of number of maneuvers required (for 1,000 meters encounters) was deemed three times as important as the measure of number of warnings required (for 3,000 meters encounters). Thus weights were updated to $w_{c1} = 0.25$ and $w_{c2} = 0.75$ using the swing weight method (Parnell and Trainor, 2009).

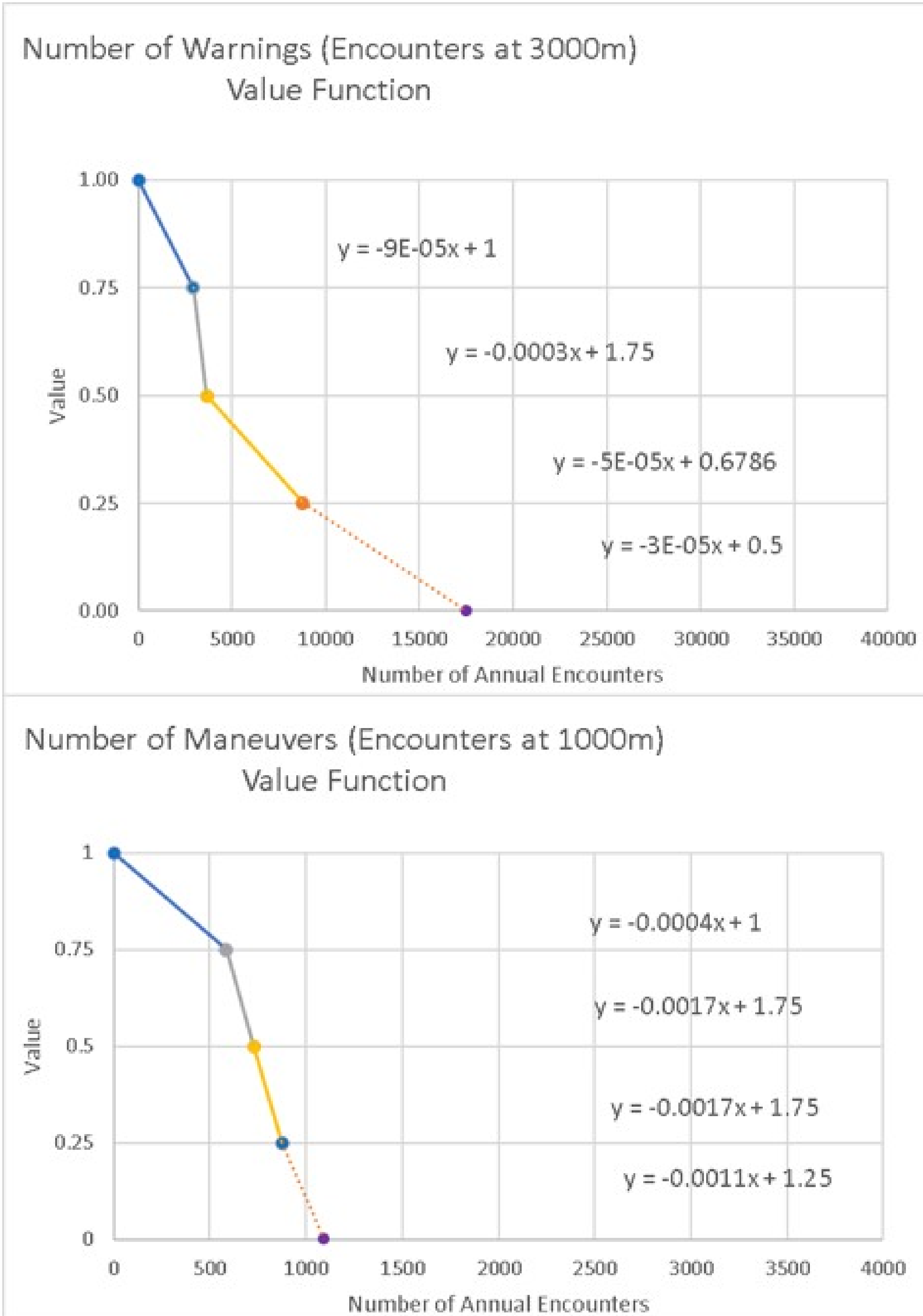


Figure 12. Congestion Value Function shapes and Equation Sets

4.3 Sensitivity Analysis

4.3.1 Shifting Weights Between Fundamental Objectives

Global weights assignments to fundamental objectives are the primary source for weight sensitivity analysis. The two fundamental objectives in this notional demonstration are maximizing mission value and minimizing congestion.

A potential starting point for global weights is equality, which in this two objective case would be 0.5 for mission and 0.5 for congestion. This typical starting point would likely not be suitable for introducing the congestion objective as a factor in orbit selection within mission design. Orbit selection value models that are purely mission focused do not generally account for congestion directly as a separate fundamental objective and would measure solely on mission attributes. This would be equivalent of this notional demonstration's mission objective having a global weight of 1 and the congestion objective having a global weight of 0. As congestion becomes more of a problem, however, the global weight of the congestion objective will start to increase, competing with the mission objective's global weight. In operational evaluations where national security mission values dominate the driving factor for orbit selection, congestion being weighted higher than mission does not make sense. Similarly, the global weight for congestion approaching equality with mission, at 0.5 for each, is unlikely for national security missions. However, such weighting schemes may someday be considered in commercial applications where money or cost is a driving factor and is defined as such as an attribute under the congestion objective.

An introductory model may define global weight for mission at 0.9 and global weight for congestion at 0.1. This could be interpreted as 90% of the orbit's value is due to mission attributes and 10% of the orbit's value is due to congestion attributes. Another way to validate these weights is to compare the relative percentages and ask if the ratio makes sense. A global weight ratio of 0.9/0.1 implies that mission

is 9 times as important as congestion. As congestion becomes more of a concerning factor, perhaps in commercial ventures and ultimately in military missions, there will be more justification towards increasing the global weight of the congestion objective.

The model demonstrated here started with equal weighting for heat maps and tested sensitivities to shifting weights at each level.

4.3.2 Sensitivity Figures

The graphs in Figure 13 show how the overall value of the orbits change when global weighting shifts importance between mission and congestion objectives. The orbits are sorted by overall score when global weighting for mission objectives are at 0.7 and global weighting for congestion objectives are at 0.3. This weighting was arbitrarily determined as an intermediary phase where mission is still slightly more than twice as important as congestion. The notional mission objective attributes of coverage and resolution are equally weighted in this scenario, and the congestion objective attributes of maneuvers are weighted at 0.75 while warnings are weighted at 0.25. The top 2 orbits, the orbit ranked near the middle (slot 3,000), and the worst ranked orbit (slot 6,479) are used to show spread of comparison for both the 20,000 and 200,000 RSO catalogues.

The two top scored orbits in the 20,000 RSO catalogue are both at 90 degrees inclination and differ only by 15 km altitude at 300 km and 315 km respectively. The scorings were nearly indistinguishable at less than 0.01% difference from each other at all weightings. However, in the 200,000 RSO catalogue, the previous number 1 orbit (best possible mission for this set at 90 degrees inclination and 300 km altitude) drops to number 2, and the previous number 2 (90 degrees inclination and 315 km altitude) drops to number 14 in the rank order due to congestion being worse. A new orbit at 90 degrees inclination and 345 km altitude takes first place.

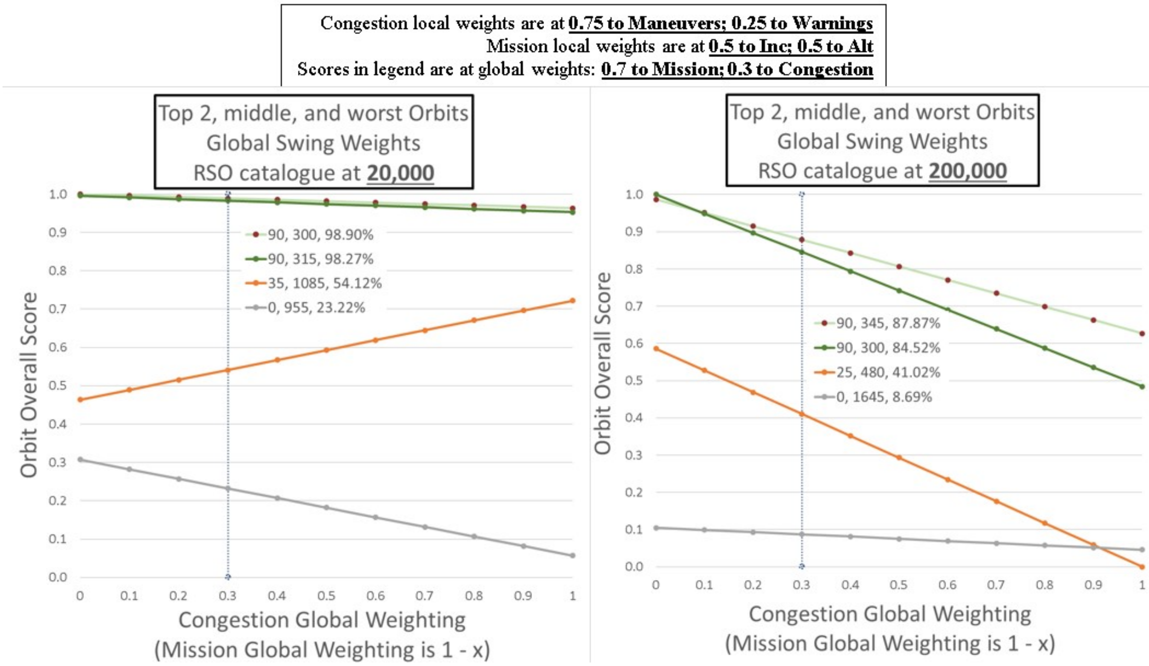


Figure 13. Sensitivity Analysis on Top 2, Middle, and Worst Orbits, for 20,000 and 200,000 RSO Catalogues

If congestion increases to ten times the current amount, then entirely new orbits are considered as most preferred. Scoring at both 20,000 and 200,000 space populations used the same value functions and local weightings for mission and congestion. Congestion scores for all orbits at 200,000 space population are worse than at 20,000 space population.

Some orbits show more tradeoffs between mission and congestion than others. This is readily found by looking at the slopes in Figure 13. Having a flat slope means that an orbit is insensitive to weight changes between congestion and mission objectives. This means that the orbit's scores for mission objectives are relatively equivalent to its scores for congestion objectives. However, a flat slope alone (insensitive to weight changes) does not make a good orbit, as demonstrated by the worst orbit on the 200,000 RSO side. The orbit at 35 degrees inclination and 1,085 km altitude has a positive slope on the 20,000 RSO side in Figure 13. A positive slope indicates that the orbit scores more poorly on mission than congestion, and its score improves when

congestion gains importance. Warnings and maneuvers for all orbits are too high to be of any value in distinguishing desired orbits at the 200,000 RSO catalogue, as shown in the steeper negative slopes of the sensitivity figure on the right. However, this result does underscore the impact of increased congestion.

One primary insight gained from sensitivity analysis is found at the crossover points between two closely ranked alternatives. An example can be seen between the top 2 scoring orbits in the 200,000 RSO, where they cross over when the congestion objective is weighted 0.1. This crossover indicates that if congestion is weighted less than 0.1, then the most preferred orbit changes. However, if it is assumed that congestion will only become more important, then the sensitivity analysis in Figure 13 confirms that at the current congestion objective weighting (0.3) and above, the current top orbit will remain more preferred than number 2.

4.3.3 Sensitivity Summary

It is important to note that some global weight selections would be unrealistic, especially when local weights are unequal, due to the relative overall weights of different objective attributes. Could minimizing maneuvers or warnings be more important than maximizing resolution or coverage? A congestion global weight that exceeded mission weight would scale the individual attributes to inconsistent meanings. If all local weights of the two mission and three congestion attributes were equal within their objective, then a congestion global weight of 0.6 and a mission global weight of 0.4 would be required to have equal local weights among all attributes. Under the same conditions with a congestion global weight of 0.7 and mission global weight of 0.3, each congestion attribute is more than 1.5 times as “important” as either mission attribute. If this global weight becomes fixed then more extreme shifts at the local weightings must occur to maintain logical consistency. This issue only becomes more

complex when many attributes and measures are used, so it is something to be aware of when designing a value hierarchy and assigning weights.

4.4 Heat Maps

Figures 14 through 17 are zoomed out heat maps visualizing how 6,479 orbits score on overall, congestion, and mission objectives. All orbits in Figures 14 through 17 have been evaluated using the same value functions. Each figure consists of three columns, (a), (b), and (c). Figures 14 and 16 are from a space population of 20,000 space objects, representing the year 2021. Figures 15 and 16 are from a space population of 200,000 space objects, representing a possible future with 10 times the congestion. Each column is a collection of 6,479 orbits, where vertical descent represents increasing altitudes from 300-2,000 km in 5 km increments, and horizontal movement from left to right represents increasing inclinations from 0-90 degrees in 5 degree increments. The left columns, labelled as (a), are the overall combined scores. The middle columns, labelled as (b), are congestion only scores. Below the middle columns is the COMSPOC's congestion graphic, provided courtesy of COMSPOC Corporation; all rights reserved. This image, shown from the top down, is for comparison of number of encounters over the same altitude and inclination ranges and 5 by 5 increments. The right columns, labelled as (c), are mission only scores. The brightest green represents a score of 1, the ideal value, and the brightest red represents a score of 0, no value added. The mission scores in (c) columns on all four Figures were designed to be exactly the same for demonstration purposes. The combined linear value functions and equal weighting for mission attributes can be seen in the color gradient of the mission only scores (c) columns. The green best mission scores in the upper right with low altitude/high inclination smoothly transition to the red worst mission scores in the lower left with high altitude/low inclination. By

design, the orbit in the upper right, with 90 degrees inclination and 300 km altitude, scores at 1 for both mission attributes and thus 1 for Mission Score, the best green. Also by design, the orbit in the lower left, with 0 degrees inclination and 2,000 km altitude, scores at 0 for both mission attributes and thus 0 for Mission Score, the worst red. The band of yellow in the middle of (c) columns shows the mid-point transition where scores fall around 0.5. Figures 14 and 15 are scores with equal weights throughout the value hierarchy. Figures 16 and 17 have been weighted the same as the sensitivity analysis: the congestion objective weighted 0.3 to the mission objective weighted 0.7, equal mission attribute weights, and the warning congestion attribute weighted 0.25 to the maneuver congestion attribute weighted 0.75. Comparing the middle columns from Figure 14(b) to Figure 16(b) and Figure 15(b) to Figure 17(b) show only minor changes in congestion scores due to shifting congestion attribute weights. The primary change is noticed in the first columns from Figure 14(a) to Figure 16(a) and from Figure 15(a) to Figure 17(a), where the overall scores are more effected by mission scores having a higher weighting. It should be noted that in this demonstration value model the mission scores, *i.e.*, all (c) columns, did not change with the increase in space population, as expected. This is because these mission scores were measured solely by altitude and inclination attributes, independent from congestion factors. However, congestion scores became unbearable throughout more altitudes when the space population increased with the same distribution, as shown by the extended red and yellow areas in Figure 15(b) compared to Figure 14(b) and Figure 17(b) compared to Figure 16(b). This increased congestion degraded the overall scores of orbits as shown in Figures 15(a) and 17(a). Weights and value functions remained the same between Figures 14 and 15, and between Figures 16 and 17, but higher space population means worse congestion scores and worse scores overall.

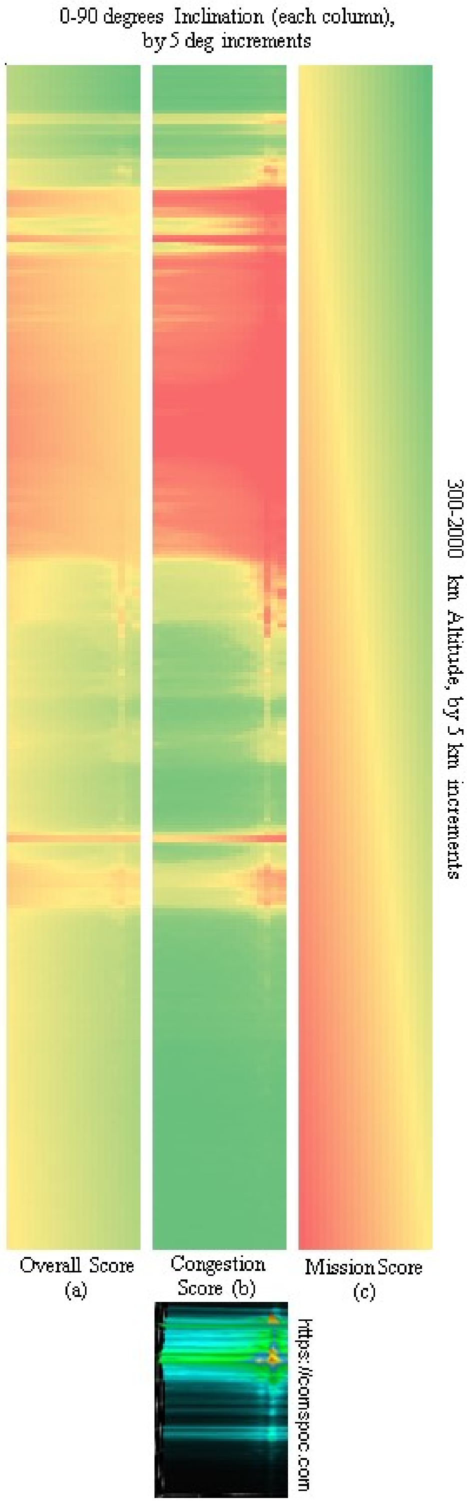


Figure 14. Heat Maps of 6,479 Orbits scores (unweighted), Population: 20 thousand

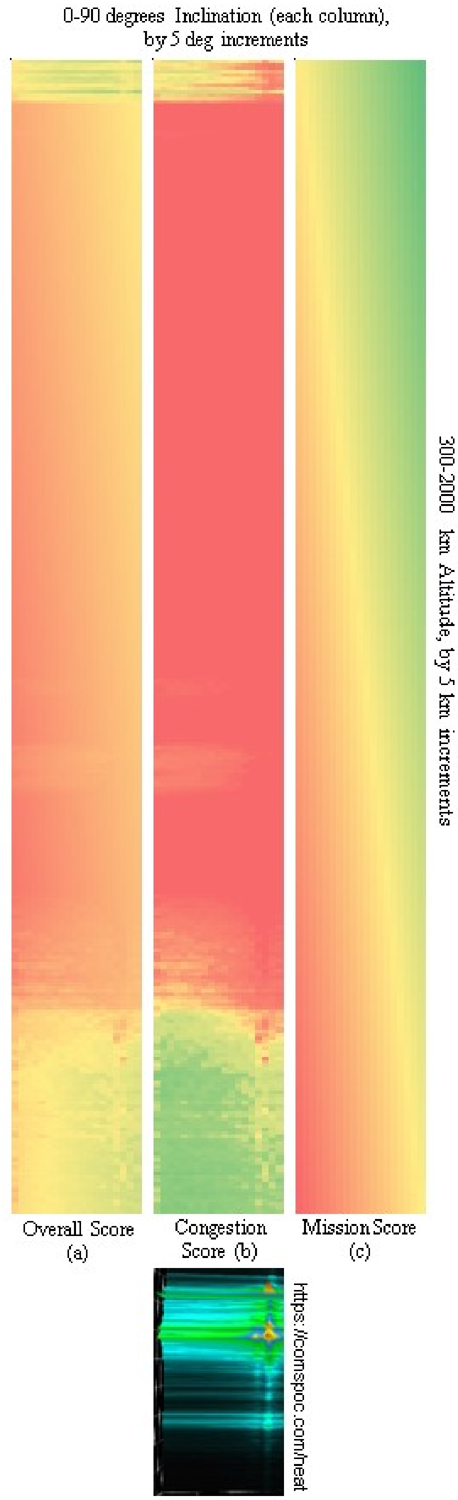


Figure 15. Heat Maps of 6,479 Orbits scores (unweighted), Population: 200 thousand

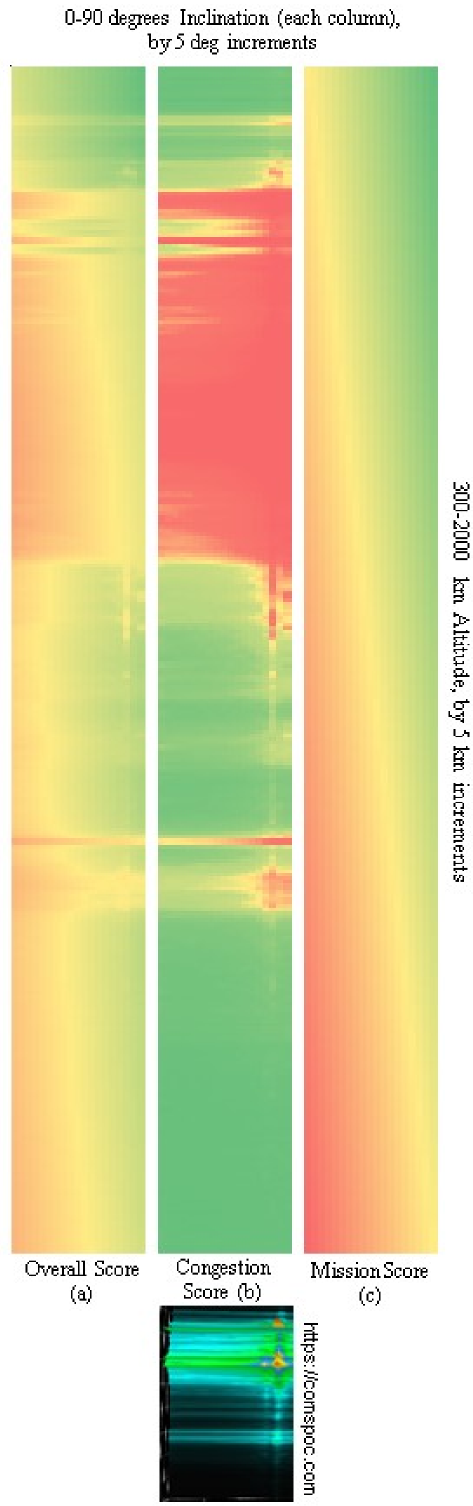


Figure 16. Heat Maps of 6,479 Orbits scores (weighted), Population: 20 thousand

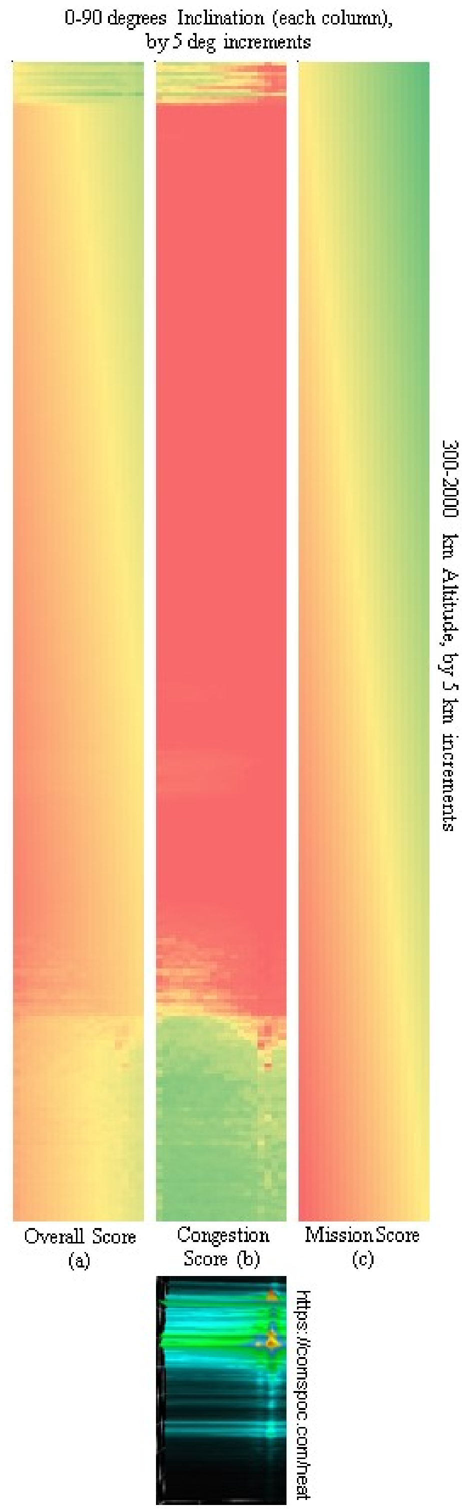


Figure 17. Heat Maps of 6,479 Orbits scores (weighted), Population: 200 thousand

4.5 Research Questions Investigated

4.5.1 Determining "near-miss" Distance

When determining whether an action is intrusive, aggressive, or hostile, one primary question is "how close is too close?" The answer to this question is driven by the particular decision maker's acceptable risk tolerance as well as how they define and measure their risk.

NASA defines orbital collision risk through their Conjunction Assessment Risk Analysis (CARA) process, explained on their website `https://satellitesafety.gsfc.nasa.gov/CARA.html`.

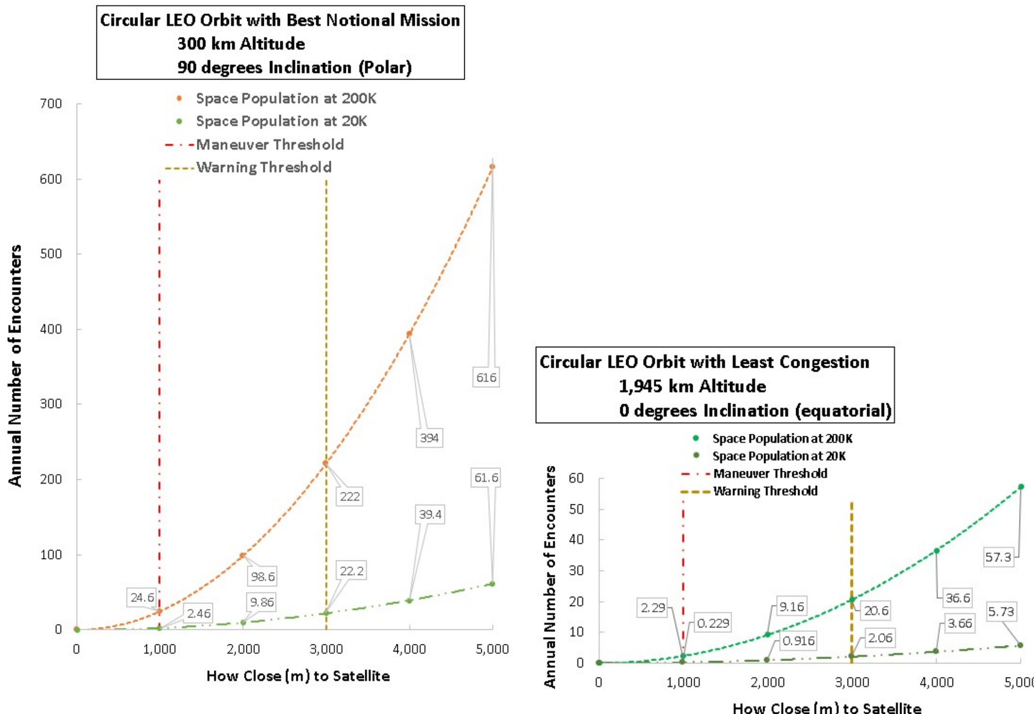
Human Space Flight (HSF), such as the mission aboard the International Space Station (ISS), has a much lower risk tolerance as compared with unmanned missions. The safety box around the ISS is much bigger than the hard body collision (HBC) box around an unmanned satellite in LEO.

The 18th Space Control Squadron (SPCS) defines parameters for reportable conjunctions in their *Spaceflight Safety Handbook for Satellite Operators.*

According to section 3.3.12 (page 41) in the FAA's *Recommended Practices for Human Space Flight Occupant Safety* (2014), "On-orbit, an operator should perform a collision avoidance maneuver if the probability of collision with any known orbital object exceeds 1E-4."

For demonstration purposes, two orbits with different congestion levels are shown in the graphs in Figure 18. Figure 18a shows the orbit with the highest mission value score from the notional demonstration presented here, at 300 km altitude and 90 degrees inclination. Figure 18b shows the orbit with the least congestion in LEO, at 1,945 km altitude and 0 degrees inclination. By comparing the measure of number of encounters, this orbit is considered the least congested orbit among the set of orbits analyzed, although its mission score was considered to be one of the least desirable in

this scenario. These graphs show the curve of how many encounters can be expected annually at various near-miss distances from these orbits, shown on the x-axis.



(a) Orbit providing the most mission value for notionally demonstrated mission

(b) Orbit with fewest encounters

Figure 18. Number of Encounters at Various Miss Distances: 2 Example Orbits

The curves in Figure 18 show how a satellite's number of encounters increase as the measurement distance from the satellite increases. In other words, as the definition of miss distance from a satellite increases, so does the expected number of encounters with other space objects it will have within that increased miss distance. Displayed on each chart are two curves representing current and potential future populations of tracked objects in space. As of February 2021, the current population of tracked space objects was 19,697 and is rounded to 20,000 objects of diameter greater than 10 cm. The potential future population of tracked space objects is estimated to be 200,000 objects. This future estimation is based on both planned satellite launches and technological improvement that "future surveillance systems

may be able to detect objects as small as 5 cm and possibly even 2 cm" (Alfano et al., 2020).

For a given miss distance on the x-axis, NEAT calculates encounters as linearly proportional with the space population. As seen in Figure 18, based on NEAT calculations a space population of 200,000 generates 10 times as many encounters as a space population of 20,000 at the same miss distance. However, while this linear proportionality may be observed if outputs were taken from NEAT at the same time, it should be noted that COMSPOC appears to update NEAT calculations over time based current satellite tracking catalogues and spatial density distributions. As mentioned in Section 3.4.2 and as shown in Figure 19, the outputs from a data capture from 12 February 2021 compared to one from 28 January 2022 showed 8 times the number of encounters for only 1.2 times increase in space population. Both data captures used the same default inputs for an orbit at 3 degrees inclination and 330 km altitude.

	Space population	**Warnings**	**Maneuvers**
12-Feb-21	19697	1.46	0.162
28-Jan-22	23752	11.7	1.3
350 days:	+ 4055	+ 10.24	+ 1.138
In <1year:	**121%**	**801%**	**802%**

21 % increase in space pop…

8-fold increase in warnings and maneuvers

Figure 19. NEAT Output Changes due to Increased Space Population Tracked, for Default Input Orbit at 330 km Altitude and 3 Degrees Inclination, from `https://comspoc.com/neat/`

4.5.2 Determining "Sovereign Space" Distance

Given the space population is increasing, and since encounters (and thus risk) increase with both space population and distance from a satellite, miss distances could be used to measure expected encounters and converted into a risk metric.

One parallel to "Sovereign Space" may be looking at the history of rules and laws that designate boundaries of international waters and sovereign coastal regions. International coastal sovereignty may have originated at the range from the coastline which a country controlled and was ultimately capable of defending, such as the range of their coastal artillery defenses. As technology improved, coastal economic regions increased as did economic extraction capabilities until they overlapped with other countries, and precise locations of international waters became contested (Fels and Vu, 2016). In some areas the contested coastline economic region extended to the connected nation's continental shelf. Arctic coastal regions are still being negotiated between Russia, Canada, and Greenland (Tranter, 2021).

By what definition do countries recognize sovereignty? The ability to defend, control, or attack a certain geographic location? An internationally recognized rule or right expected to be respected? Rules of engagement in air and at sea may be an analogy to be used for space norms of behavior.

Some effects of congestion will require international treaty, policy, and safety standards. The purpose of laws in place are to clarify acceptable actions by deterrence, prevention, and if needed, punishment such as sanctions.

The graphs in Figure 18 may provide insight to future "Sovereign Space" speculations. As referenced in section 2.2.8, as OOS and OSAM capabilities become more prevalent, the question "how close will be too close?" becomes more important.

4.6 Summary of Results

It can be seen that an orbit scored on mission value alone, when evaluated for congestion value and combined, can drastically change which orbit provides the best overall value. With an increase in congestion via a rise in space population, an orbit with a poor mission score, *i.e.*, higher altitude for this example, may become more preferable overall due to a necessity for less congestion and risk of impact.

V. Conclusions and Recommendations

5.1 Contributions of this Thesis

This thesis focused on addressing the questions:

- How are orbits selected?
- What gives orbits value?
- How can orbital congestion be measured?
- What is the definition of a near-miss on orbit?

This thesis addressed these questions by presenting a value framework to include mission and congestion factors to use in future orbit evaluations. This thesis developed a method to evaluate multiple orbits according to a decision maker's objectives. These objectives can be made as complex as the analyst requires to properly analyze the mission being studied. Results of this evaluation provides insight into which orbit is most suited to the decision maker's mission and congestion needs.

5.2 Considerations for Improvement

This section addresses some considerations for alternate practice in future iterations. Due to the potential overwhelming importance of not having any collisions may have, it may be preferable to convert the collisions measure under the congestion objective into an indicator variable in the overall objective function. This would shift the mindset of this measure from adding value to an alternative to becoming an overall problem constraint. This indicator variable use could help eliminate unfavorable alternatives when scoping orbits for selection as the modeler iterates the decision and evaluation process. Another alternative method would be making the overall objective function a multiplicative scoring instead of a weighted sum.

5.3 Recommendations for Future Direction

This thesis focused on circular orbits in LEO. While the publicly available tool used in this thesis, NEAT, only calculates circular orbits, there may be other tools that measure congestion for evaluating elliptical orbits, or orbits above the LEO regime.

The methodology presented in this thesis could also be applied in other areas within and outside of orbit selection. International standards for satellite safety include end of life requirements that need to be met by any launching entity. These international standards encourage environmental stability of orbital regimes for everybody. Due to the prolonged and remote nature of satellite deployment and operations, end of life requirements need to be planned well before launch and have ripple effects throughout the entirety of spacecraft mission design. Appropriate consideration for number and magnitude of maneuvers required directly affects the available lifetime of a satellite's limited fuel supply. Every satellite has planned and unplanned maneuvers such as station keeping or re-positioning, and collision avoidance. Each expense of fuel limits the satellite's future capability to maneuver or transfer orbits.

Further analysis can be performed to legally define the "sovereign space" surrounding a nation's satellite, akin to territories bordering international waters or airspace. An investigation into different definitions of a satellite "near-miss" is imperative to the establishment of behavioral norms. Legally definitive aggressive and passive behaviors, agreed upon via treaty or otherwise, would reduce the analysis involved in deciphering intent behind actions and events. This is especially true during rendezvous and proximity operations (RPO) and for conjunction analysis.

Satellite constellations are constantly being updated with newer satellites with better capabilities. With limited orbital slots to provide the most mission value, companies and nations have a set cover problem when it comes to matching the

highest priority orbital position with the right level of available capability. There also exists a tradeoff space between value added without movement, and value minus cost of moving an older satellite. If a higher fidelity tool were used to measure near-term congestion, this methodology could be used to calculate relative values of congestion scores to be input for satellite mid-life orbit changes, which require costly delta-v. Higher resolution congestion measurement tools would also be useful in determining launch windows. As congestion becomes a more important safety factor, the launch window matching a satellite to a particular orbit needs to also be below a tolerable risk level in regard to present congestion or probability of collision over the given launch site.

5.4 Final Summary

As congestion increases, its effects will become more critical. As space becomes a more contested environment, the need for spacecraft rules of engagement and "sovereign space" will become more critical. More congested space will require methods to allocate orbits and perhaps treaties to regulate space clean-up operations. The modeling approach proposed in this thesis suggests a framework for measuring and balancing the potential negative impact of opting for a mission effective but congested orbit. This approach could be used to identify high value orbits critical to controlling space. This thesis introduced a methodology to quantitatively analyze some of the questions exacerbated by congestion in space.

Appendix A: VBA Script

The VBA script used to pull data from the NEAT website is attached in this appendix as a PDF. Comments are in green and the main inputs and outputs are in red.

```
Option Explicit
'Authors: Capt Anthony Correale and Dr. Jeff Weir
'This VBA subroutine allows automatic collection of a web tool's outputs
     and writes them to an excel sheet.
'It iterates through user programmed inputs by submitting them and
     collecting outputs provided from the webpage for each iteration.


Sub NEATpull()

'Dimension all variables:
    Dim ieApp As Object          'environment for internet explorer
    Dim ieDoc As Object          'object to contain all html interfaces
    Dim theForm As Object        'object used to submit inputs to webpage
    Dim webInputs As Object      'object to store html input tags and values
    Dim webOutputs As Object     'object to store html outputs and values
    Dim webPeriod As Object      'object to store html selector tag and
        value
    Dim rownum As Integer        'current row number
    Dim NumRows As Integer       'total number of rows
    Dim i As Single              'inclination index
    Dim a As Single              'altitude index
    Dim j As Single              'threshold index
    Dim RSO As Single            'Resident Space Objects (number of objects
        tracked in orbit)
    Dim numSats As Single        'number of satellites in constellation
    Dim webwarnings As String
    Dim webmanuevers As String
    Dim webcollisions As String
    Dim outputArray() As Variant
    Dim StartTime, FinishTime, TotalTime
    Dim itr As Integer           'iteration number


'If used, show progress indicator
'UserForm1.Show

    Application.ScreenUpdating = False

 'Option is set by default to start lists at 0; add 1 to list inputs and
      subtract one when pulling data
 'Define total number of rows (make a named cell on Inputs sheet)
    'NumRows = Worksheets("Inputs").Range("numRows")

' Record starting time
  StartTime = Timer

  'Create a new instance of ie (internet explorer)
    Set ieApp = CreateObject("InternetExplorer.Application")
    ieApp.Visible = False
    'ieApp.Visible = True 'for debugging

    'go to your website
    ieApp.Navigate "http://www.comspoc.com/neat/"
    'let website load
    Do While ieApp.Busy: DoEvents: Loop
    Do Until ieApp.ReadyState = 4: DoEvents: Loop

    'Get lists of html tags
    Set ieDoc = ieApp.Document

    'Get the link to the javascript function.  They call it form1
    Set theForm = ieDoc.forms("form1")

    'Get html input tags as list
    Set webInputs = ieDoc.getElementsByTagName("input")
```

```
    'Get current raw paragraph for text outputs: item 11
    'Set webOutputs = ieDoc.getElementsByTagName("Div").Item(11)

    'Get period selector tag name from webpage
    Set webPeriod = ieDoc.getElementsByTagName("select").Item(0)

    rownum = 2  'define starting row for writing outputs
    itr = 1     'set starting iteration number for tracking purposes

    'Set webpage period selector to days, months, or Years:
    webPeriod.Value = webPeriod.Item(2).Value 'item(0)=days, item(1)=months
         , item(2)=Years
        Sheet3.Range("H1") = webPeriod.Value ' "days" or "months" or "Years
             "    'writes period onto sheet
        Sheet3.Range("H2") = webInputs("main_periodValue").Value  'writes
             how many periods onto sheet

'Change other webpage start conditions as desired:
    'webInputs("main_txt_numberOfSatellites").Value = Sheet1.Range("NumSats
         ")                 '64     'main_txt_numberOfSatellites; item 8
    'webInputs("main_txt_warningThreshold").Value = Sheet1.Range("
         Thresholds").Value2(1, 1)   '3000   'main_txt_warningThreshold, (m)
    'webInputs("main_txt_manueverThreshold").Value = Sheet1.Range("
         Thresholds").Value2(2, 1)  '1000   'main_txt_manueverThreshold (m)
    'webInputs("main_txt_collisionThreshold").Value = Sheet1.Range("
         Thresholds").Value2(3, 1) '5      'main_txt_collisionThreshold (m)

'Set webpage inc, alt and RSO to predefined values
    'Set starting inclination for webpage
    'webInputs("main_txt_inclination").Value = Sheet1.Range("
         InclinationInputs").Value2(1, 1)  '3      'main_txt_inclination (
         deg) 16
        i = webInputs("main_txt_inclination").Value
            Sheet3.Cells(rownum, 2) = i             'write inclination to
                 current row in column 2

    'Set starting altitude for webpage
    'webInputs("main_txt_altitude").Value = Sheet1.Range("AltitudeInputs").
         Value2(1, 1)    '300    'main_txt_altitude (km above equator) 18
        a = webInputs("main_txt_altitude").Value
            Sheet3.Cells(rownum, 3) = a             'write altitude to
                 current row in column 3

    'Set RSO population (number of objects in space) as desired; default is
          19,697; I rounded to 20,000 for consistency
    webInputs("main_txt_userSpecifiedResidentSpaceObjects").Value = 20000 '
         Sheet1.Range("SpacePop")
        RSO = webInputs("main_txt_userSpecifiedResidentSpaceObjects").Value
            Sheet3.Cells(rownum, 7) = RSO             'write RSO to current
                  row in column 7

    'Set number of satellites on webpage
    'webInputs("main_txt_numberOfSatellites").Value = 64
        'get number of satellites used on webpage
        numSats = webInputs("main_txt_numberOfSatellites").Value
            Sheet3.Cells(rownum, 9) = numSats         'write current number
                  of sats to current row in column 9

    'Initiate outputArray as (total number of rows) by 6 columns to store
         all values (itr,inc,alt,warn,man,col)
    'ReDim outputArray(NumRows - 1, 5)


'Loop through desired input parameters:
'Change these lines to use named input ranges from sheet 1
  'For a = Sheet1.Range("AltitudeInputs").Value2(1, 1) To Sheet1.Range("
       AltitudeInputs").Value2(2, 1) Step Sheet1.Range("AltitudeInputs").
       Value2(3, 1)    'loop altitudes
```

```
'For i = Sheet1.Range("InclinationInputs").Value2(1, 1) To Sheet1.Range
    ("InclinationInputs").Value2(2, 1) Step Sheet1.Range("
    InclinationInputs").Value2(3, 1) 'loop inclinations

'Inclinations: Define range and increment size to iterate for pulling
 For i = 70 To 90 Step 5

    'Altitudes: Define range and increment size to iterate for pulling
     For a = 300 To 2000 Step 5

        'Set current inclination index to the webpage input
        webInputs("main_txt_inclination").Value = i     '
             main_txt_inclination (deg) 16

        'Set current altitude index to the webpage input
        webInputs("main_txt_altitude").Value = a    'main_txt_altitude
             (km above equator) 18

    'Set other input values using webInputs()
    ' note: these numbers may not match given item numbers; recommend
         using text input as string tag
    '   6  main_periodValue
    '   8  main_txt_numberOfSatellites
    '   5  main_txt_warningThreshold   '11
    '   7  main_txt_manueverThreshold  '13
    '   9  main_txt_collisionThreshold '15
    '   11  main_txt_inclination
    '   13  main_txt_altitude
    '   14  main_txt_userSpecifiedResidentSpaceObjects

        'this block can be substituted in to iterate through threshold
             values
        'For j = 0 To 5010 Step 30
        '  webInputs("main_txt_warningThreshold").Value = j + 20
        '  webInputs("main_txt_manueverThreshold").Value = j + 10
        '  webInputs("main_txt_collisionThreshold").Value = j

    'Recalculate form based on your input (provide new set of outputs
         per iteration)
    theForm.submit

     'Let page load
        Do While ieApp.Busy: DoEvents: Loop
        Do Until ieApp.ReadyState = 4: DoEvents: Loop
     'Alternate method:
        'Application.Wait (Now + TimeValue("0:00:03"))

     'Reset VBA objects to match webpage tags
        Set theForm = ieDoc.forms("form1")
        Set webInputs = ieDoc.getElementsByTagName("input")
        Set webOutputs = ieDoc.getElementsByTagName("Div").Item(10) ' a
             lot of "Div" Tags to sift through as Items in object

    'get new calculated values for current iteration
        webwarnings = webOutputs.all.Item(4).innerText
        webmanuevers = webOutputs.all.Item(6).innerText
        webcollisions = webOutputs.all.Item(8).innerText

    'pull desired text out of paragraph for number of warnings,
         maneuvers, collisions:
    webwarnings = Right(webwarnings, Len(webwarnings) - InStr(1,
         webwarnings, ":") - 1)
    webmanuevers = Right(webmanuevers, Len(webmanuevers) - InStr(1,
         webmanuevers, ":") - 1)
    webcollisions = Right(webcollisions, Len(webcollisions) - InStr(1,
         webcollisions, ":") - 1)

    'Write each iteration info to an Excel row on sheet 3:
```

```
        Sheet3.Cells(rownum, 1) = itr           'iteration number col 1
        Sheet3.Cells(rownum, 2) = i             'inclination column 2
        Sheet3.Cells(rownum, 3) = a             'altitude column 3
        Sheet3.Cells(rownum, 4) = webwarnings   'col 4
        Sheet3.Cells(rownum, 5) = webmanuevers  'col 5
        Sheet3.Cells(rownum, 6) = webcollisions 'col 6


        'Alternate method: store each iteration in a VBA array prior to
            writing all at once
'        outputArray(rownum - 2, 0) = itr          'iteration number col 1
'        outputArray(rownum - 2, 1) = i            'inclination column 2
'        outputArray(rownum - 2, 2) = a            'altitude column 3
'        outputArray(rownum - 2, 3) = webwarnings  'col 4
'        outputArray(rownum - 2, 4) = webmanuevers 'col 5
'        outputArray(rownum - 2, 5) = webcollisions 'col 6

            'iterate row and count
            rownum = rownum + 1
            itr = itr + 1

            'Next j  'iterate threshold value loop
        Next a       'iterate altitude loop
    Next i           'iterate inclination loop

'if used, close progress bar
'Unload ufProgress


'calculate time taken
FinishTime = Timer
TotalTime = FinishTime - StartTime

'If array used, output array to sheet
'Sheet4.Range("A3", Sheet3.Range("A3").Offset(NumRows - 1, 4)) =
    outputArray()

'output time to sheet
Sheet3.Range("I2") = TotalTime


Application.ScreenUpdating = True

'quit internet explorer environment
ieApp.Quit

End Sub
```

Appendix B: Orbital Calculations

The orbital mechanics calculations of speed and period based on altitude are attached in this appendix.

Circular LEO parameters calculator (no atmospheric drag)

Altitude (mi)	**Altitude** (km)	**Orbital Radius, R_o** (km)	**Orbital Circumference** (km)	distance(km)/ degree	**Speed (km/s)** =SQRT(G*M/(R_o*1000)) /1000	Speed (mph)	Period: Circumference/Speed (seconds)	(minutes)	(hours)	(# per day)
Earth Surface			Earth average		Escape Velocity					
0	0	6,370	40,024	111	7.91	17,693				
LEO:										
186	300	6,670	41,909	116	7.73	17,290	5,422	90.37	1.51	15.94
249	400	6,770	42,537	118	7.67	17,162	5,544	92.41	1.54	15.58
311	500	6,870	43,165	120	7.62	17,037	5,668	94.46	1.57	15.24
373	600	6,970	43,794	122	7.56	16,914	5,792	96.53	1.61	14.92
435	700	7,070	44,422	123	7.51	16,794	5,917	98.62	1.64	14.60
497	800	7,170	45,050	125	7.46	16,676	6,043	100.72	1.68	14.30
559	900	7,270	45,679	127	7.40	16,561	6,170	102.83	1.71	14.00
621	1,000	7,370	46,307	129	7.35	16,449	6,298	104.96	1.75	13.72
684	1,100	7,470	46,935	130	7.30	16,338	6,426	107.10	1.79	13.44
746	1,200	7,570	47,564	132	7.26	16,230	6,556	109.26	1.82	13.18
808	1,300	7,670	48,192	134	7.21	16,124	6,686	111.43	1.86	12.92
870	1,400	7,770	48,820	136	7.16	16,020	6,817	113.62	1.89	12.67
932	1,500	7,870	49,449	137	7.12	15,917	6,949	115.82	1.93	12.43
994	1,600	7,970	50,077	139	7.07	15,817	7,082	118.03	1.97	12.20
1,056	1,700	8,070	50,705	141	7.03	15,719	7,216	120.26	2.00	11.97
1,118	1,800	8,170	51,334	143	6.98	15,623	7,350	122.51	2.04	11.75
1,181	1,900	8,270	51,962	144	6.94	15,528	7,486	124.76	2.08	11.54
1,243	2,000	8,370	52,590	146	6.90	15,435	7,622	127.03	2.12	11.34
MEO:										
3,107	5,000	11,370	71,440	198	5.92	13,243	12,067	201.12	3.35	7.16
6,214	10,000	16,370	102,856	286	4.93	11,037	20,847	347.45	5.79	4.14
9,321	15,000	21,370	134,272	373	4.32	9,660	31,094	518.24	8.64	2.78
12,427	20,000	26,370	165,688	460	3.89	8,696	42,622	710.37	11.84	2.03
15,534	25,000	31,370	197,104	548	3.56	7,973	55,302	921.71	15.36	1.56
18,641	30,000	36,370	228,519	635	3.31	7,404	69,038	1,150.63	19.18	1.25
21,748	35,000	41,370	259,935	722	3.10	6,943	83,753	1,395.88	23.26	1.03
GEO:										
22,245	35,800	42,170	264,962	736	3.07	6,876	86,194	1,436.57	23.94	1.00
22,287	35,867	42,237	265,383	737	3.07	6,871	86,400	1,439.99	24.00	1.00

Earth Radius, R_e:	6370	km
G (universal gravitational constant)	6.6726E-11	N* m^2/ kg^2
M (Earth's mass)	5.97E+24	kg

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14. ABSTRACT

Low Earth Orbit (LEO) is becoming more congested, which increases the risk to space missions. Decision makers will need to consider this increase in congestion as an increased risk within their mission engineering process. This thesis proposes a methodology to create and implement a value structure that quantitatively scores a range of orbits based on congestion factors of each orbit and how well each orbit meets mission requirements. This thesis demonstrates this methodology on a set of circular LEO orbits defined by altitude and inclination, and scores this illustrative scenario based on notional mission measures and expected number of encounters as congestion measures. These scores are analyzed for sensitivity to changes in orbit scoring recommendations if the decision maker were to change the importance levels between mission and congestion factors. For any given mission definition, this orbit scoring methodology can be used to identify high value orbits that would be critical to controlling space.

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