On-Orbit Servicing System Architectures for Proliferated Low Earth Orbit Constellations

by

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Abstract

On-orbit servicing (OOS) presents new opportunities for refueling, inspection, repair, maintenance, and upgrade of spacecraft (s/c). OOS is a significant area of need for future space growth, enabled by the maturation of technology and the economic prospects. This congestion is leading s/c operators to explore how they can leverage OOS. OOS missions for s/c in geostationary orbit (GEO) are currently underway. This is being driven by the closure of the business case for refueling long lived monolithic chemically propelled GEO assets. However, there are currently no plans for OOS of low-earth orbit (LEO) s/c, aside from technology demonstrations, because of their shorter design life and lower cost. It will become particularly important to enable the servicing of LEO s/c as the industry shifts its focus towards LEO. Designing OOS systems for LEO constellations differs from that of GEO based systems, this difference is attributed to LEO's proliferation of satellites, environmental effects (J2 nodal precession, drag), and different constellation patterns. Satellite constellations in LEO are becoming more distributed due to increased access, distributed risk, flexibility, and cost. OOS of s/c may enable the reduction of requirements on subsystems such as safety and the need for redundancy. These requirement reductions will enable lower risks, lower costs, and increased system resilience. This paper analyzes the benefits of OOS in proliferated LEO constellations. Several OOS system architectures are modeled in various scenarios; in each system architecture the model will vary qualities such as mass, altitudes, time, propulsion system, maneuver, and type of service. The objective of the model will be to optimize for cost, time, and utility to generate a tradespace for an OOS system architecture. OOS provides higher utility over the comparative alternative of using spare satellites in some scenarios. The utility of OOS provides even more utility when considering failure rates of satellites and allowing for an increase in failure rates when adopting an OOS system.

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1. Introduction

1.1 Motivation

Over 70% of all operational satellites currently operate between 160 and 2,000 km, in Low Earth orbit (LEO) [1]. Reusable space launch vehicles have decreased the cost to place satellites into orbit and as a result greatly increased the number of satellites in orbit. For the first time in history satellite operators are deploying hundreds and thousands of satellites, in order to form large-scale constellations called proliferated LEO constellations (pLEO) [2]. The servicing of satellites in orbit, also known as on-orbit servicing (OOS), is particularly advantageous for high-value or exotic satellites [3–5]. Most high-value satellites reside in higher altitudes at ~35,000 km; in geosynchronous orbit (GEO) [6]. LEO is a much easier orbit to access since the radius is much closer to earth compared to each of the other orbits as seen in Figure 1-1. Since satellites in LEO are typically much less expensive than those in GEO, they have not been the primary focus of OOS studies and applications. However, the large quantity of satellites in LEO provide advantages in economies of scale and scalability for OOS. This particular attribute to LEO based constellations opposed to GEO based ones provide areas of exploration for different OOS systems to not just extend satellite utility; but to enable new space system architectures.

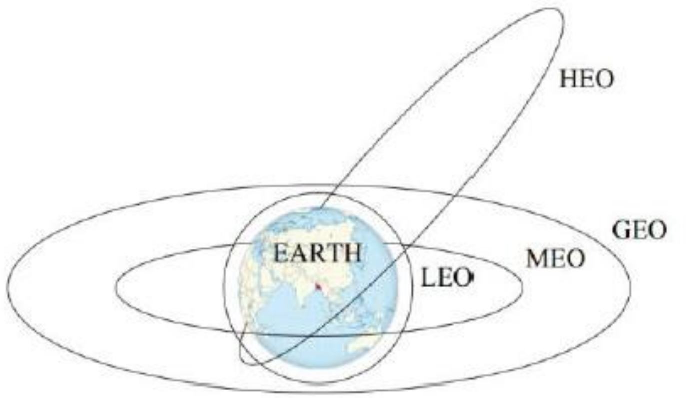

Figure 1-1 Types of orbits, not to scale. [7].

1.1.1 The Shift from GEO to Proliferated LEO

GEO has been the dominant place for space based broadband communication systems. The higher orbit grants the opportunity for large areas of coverage for a single satellite which can be seen in Figure 1-2 and Figure 1-3. A GEO constellation can achieve global coverage with as few as 3 equally spaced satellites. However, this high orbit also comes with a penalty of long latency times due to the significant distance that electromagnetic waves must travel between Earth and the satellite.

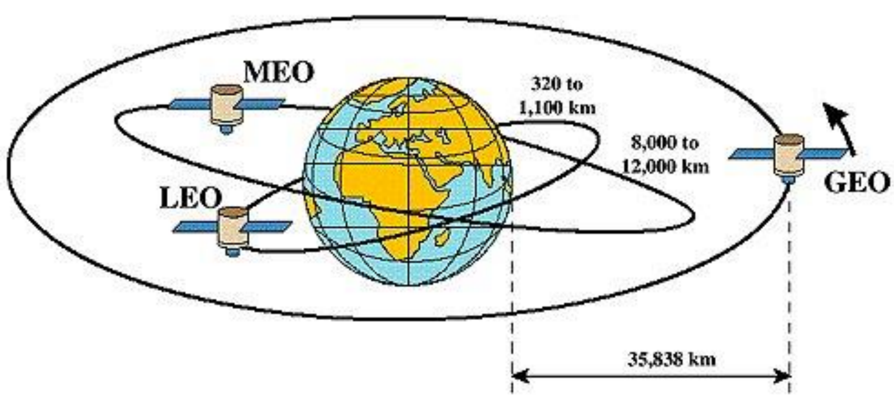

Figure 1-2 Magnitudes and classification of altitudes of orbits [7]

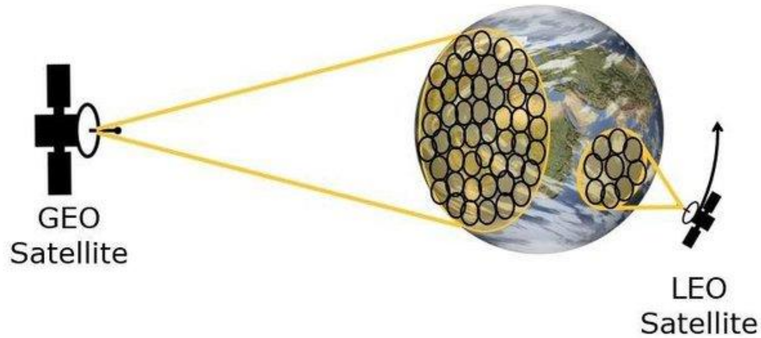

Figure 1-3 Example of terrestrial coverage of GEO vs LEO satellites [8]

Due to the significant launch costs as a result of distance, satellite operators heavily invest in their GEO satellites to ensure they have a long design life to provide as much operational utility and revenue generation as much as possible. Secondly, LEO constellations were deemed unfeasible or cost prohibitive due to the sheer number of satellites that would need to be launched and managed. An example LEO constellation is seen in Figure 1-4. Additionally, these GEO satellites must have significant investment in more robust communications systems to compensate for the large distance the signals must cover. This paradigm has been shifted as a result of several factors over the last several decades.

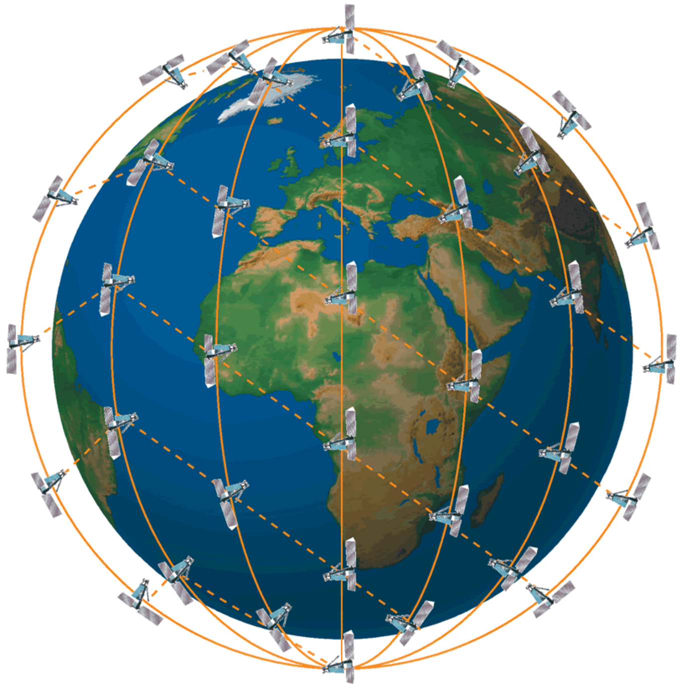

Figure 1-4 Example of a LEO satellite constellation [9]

1. Commercial space launch - Increased access to space by commercial space launch providers like Orbital ATK (OATK, now Northrop Grumman), SpaceX, and Rocket Lab over the last few decades have greatly driven down the cost to enter the space market as illustrated in Figure 1-5. This has enabled many new companies and business models to enter the market [10].

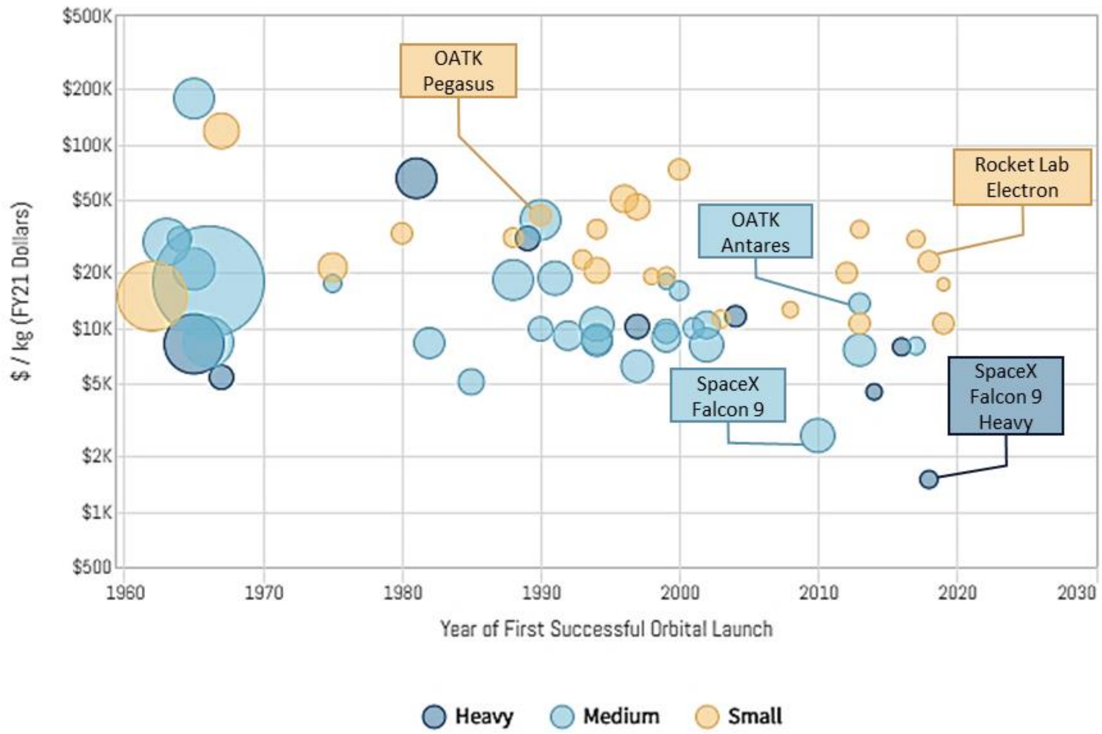

Figure 1-5 Cost of various launch vehicles per kg based on year of launch [11]

2. Technology development – The need for physical or mechanical manipulation of directional dish antennas has been made obsolete with phased array antennas. These phased array antennas utilize electromagnetic waves and interference beam form and point their signals as seen in Figure 1-6. High throughput satellites (HTS) are now being deployed to leverage Ka band's higher frequency over Ku band which is illustrated in Figure 1-7. Ku band is primarily used in GEO satellites where Ka band's shorter wavelength is a disadvantage [12]. Deploying to LEO allows HTS to satisfy increasing bandwidth demands with its higher throughput.

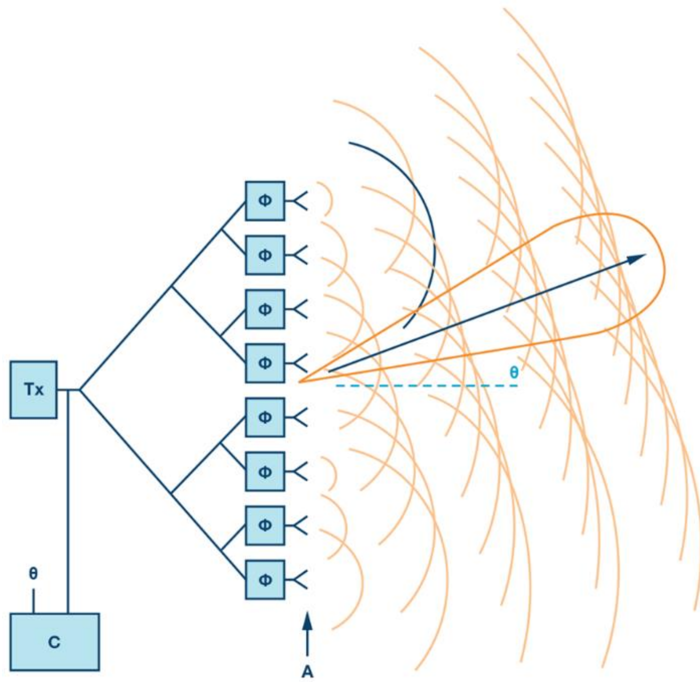

Figure 1-6 Phased array antenna example of beam forming [13]

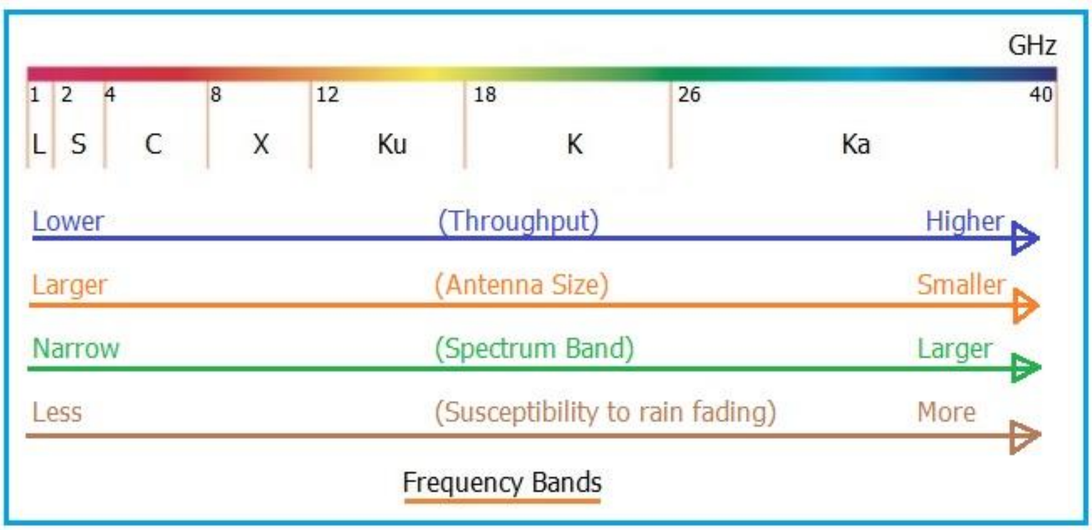

Figure 1-7 Spectrum comparison of frequency bands [14]

Autonomous systems and robotic control of spacecraft has also made improvements to the point where managing large constellations are now more feasible[15]. Due to the distance from the Earth ground controlled robotic systems were not feasible due to the latency of any feedback control system involving a human in the loop. Programs like Orbital Express demonstrated the capabilities enabled by robotic autonomous systems in OOS activities [16].

3. Funding – There has been significant availability of funding and capital over the last several years due to the increased interest in space and positive economic conditions, from 2019-2020 alone venture capital investments totaled over $4b [17]. Government spending also plentiful as over $16 billion dollars in federal subsidies is currently available to provide broadband services to rural communities [18].

1.1.2 What is On-Orbit Servicing?

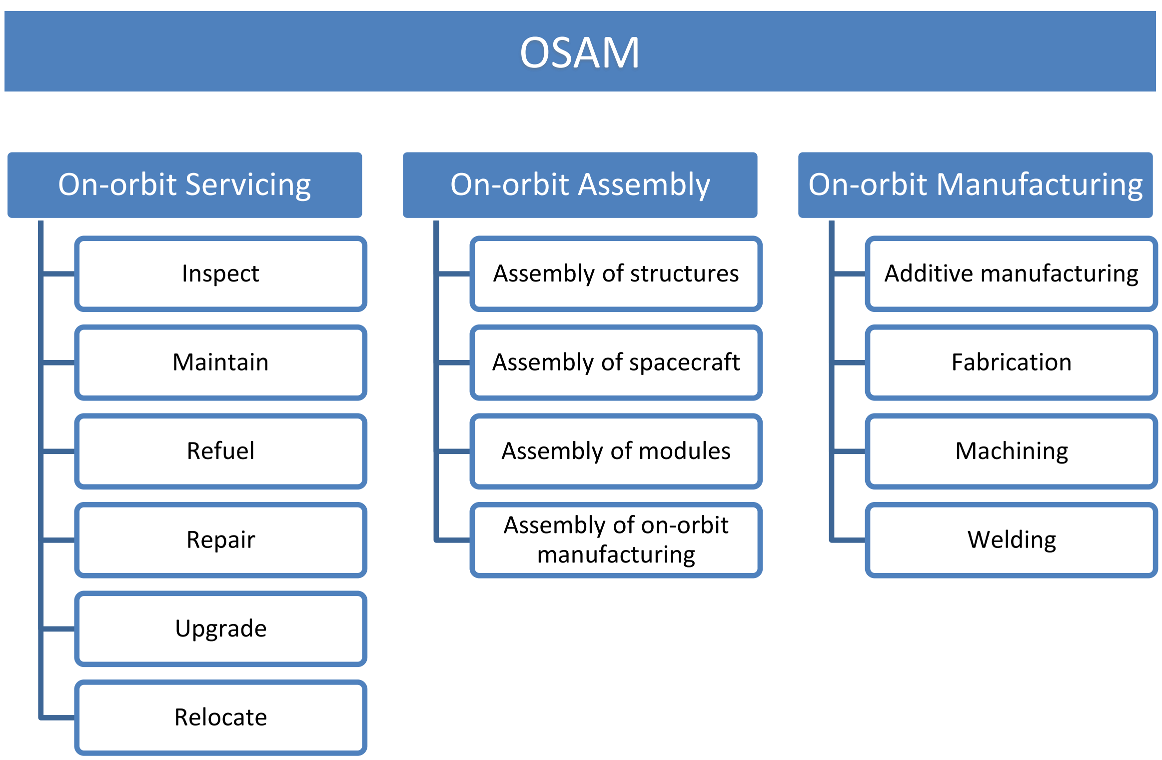

Figure 1-8 Taxonomy of On-orbit Servicing, Assembly, and Manufacturing (OSAM) [19,20]

The current size, mass, and capabilities of spacecraft today are severely limited by the launch vehicles that are available. Satellites are designed for a finite lifespan and are disposed of either by deorbiting into the atmosphere, or left drifting in orbit when they retire or maneuvered into a graveyard orbit. However, satellite design, constellation configuration, and lifecycle management remain largely unchanged since the very first space launch. The status-quo remains with the one-time use and disposable nature of space systems.

Increased access to space has contributed to congestion, complexity, and competition within the space market, these factors demand more flexible systems that can be augmented to meet the dynamic needs of the market. OSAM offers new flexible options in addressing these needs. OOS is one of three categories of which make up OSAM as defined in Figure 1-8. This thesis focuses exclusively on OOS and exploring its tradespace in LEO. OOS enables the restoring service, extending satellite lifetimes, upgrading capabilities, mitigating risks, and reducing space system requirements for future constellations. OOS encapsulates the ability for a servicing spacecraft to inspect, refuel, maintain, rectify anomalies, upgrade, or tug a target spacecraft. Being able to execute these activities permits satellite operators a plethora of options in satellite operations.

OOS enables continued operational utility and revenue generation from existing satellites. There is not any other industry where we build complex machines for single use and then dispose of them when a single component has failed or fuel has been exhausted. Space systems are some of the most robust, expensive, and reliable systems that humankind has ever created. This represents the ideal platform to service in order to continue returns on investment, development, and deployment. As the world shift towards sustainability and more efficient use of its resources, OOS provides a well-suited means concept to address gaps in satellite utility.

Northern Sky Research estimates that $6.2 billion dollars in cumulative revenue opportunity exists for OOS by 2030 as shown in Figure 1-9 [21].

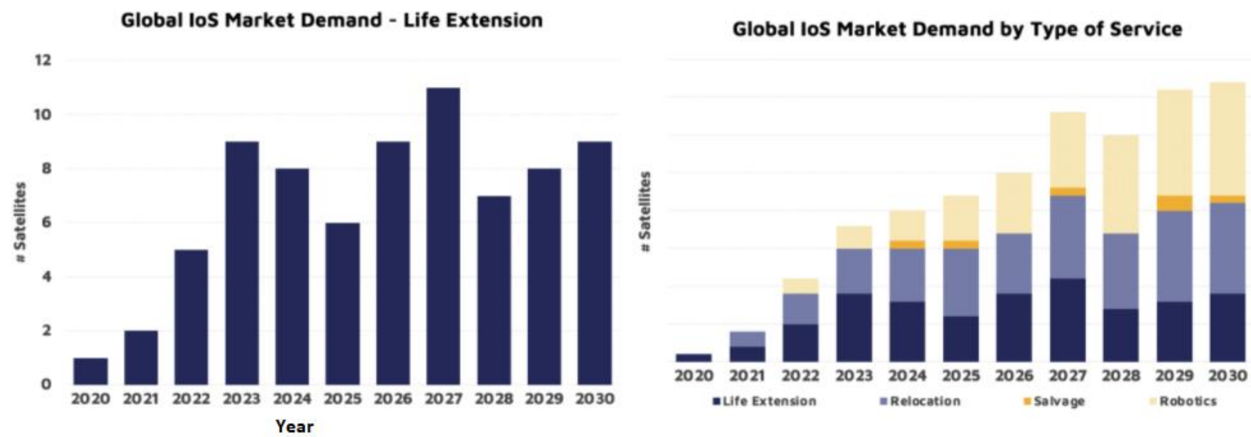

Figure 1-9 Estimated demand for In Orbit Servicing (IoS)/OOS [21]

1.1.3 Why robotic OOS?

Nearly all satellites launched into space have been designed for a finite life span and without the ability or consideration for servicing. The harsh conditions for satellite deployment experienced during launch create some of the most significant system requirements for satellites, these conditions include shock, vibration, and thermal loads. Due to the robust requirements which satellites are built to their payloads, components, and sub-systems largely outlive their design life [22].

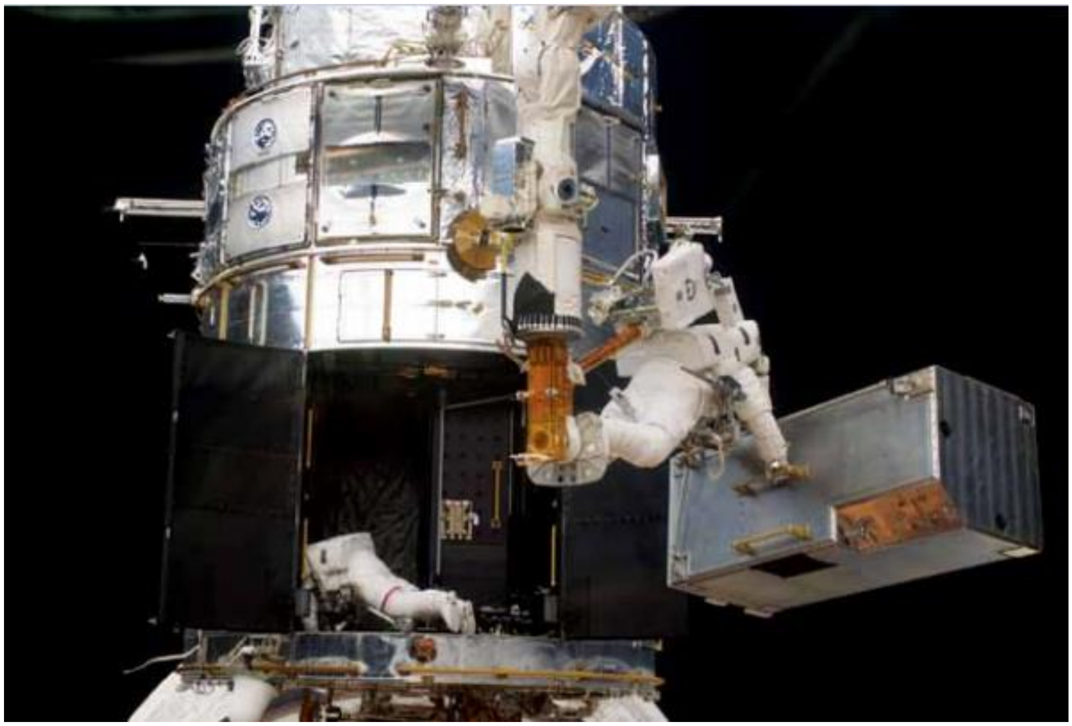

Figure 1-10 The Hubble space telescope's first servicing mission by STS 61 [19]

There have been several missions which have taken place to service existing satellites in orbit which will be reviewed later. Most of these servicing missions were executed by human crewed missions aboard the space shuttle which operated from April 12, 1981 to July 21, 2011 [23]. Figure 1-10 is a picture from one of the most famous servicing missions from the shuttle program which repaired the defective lenses, gyroscopes, electrical control units, and solar arrays [24]. OOS provided several benefits in recovering or enhancing the capabilities of some satellites, however the cost and risk were enormous. Due to the loss of two space shuttles and 14 crew members, the space shuttle program became too costly and risky which resulted in its retirement.

Robotic and autonomous OOS provides significant advantages in both cost and risk. Human life support systems, crew safety, abortion capabilities, and risk mitigation create significant costs to crewed spaceflight programs. Robotic OOS could achieve the same capabilities of a crewed mission as was proposed in the Hubble Robotic Servicing Vehicle shown in Figure 1-10 [25,26]. We are now at a point in history where robotic sensing, manipulation, control, and autonomy have advanced to the point where robotic OOS is technologically feasible. These reductions in both the costs as well as the technological capabilities of robotic OOS make it appealing for exploring what new system architectures can be enabled. This thesis exclusively covers robotic and autonomous OOS, crewed missions are not considered.

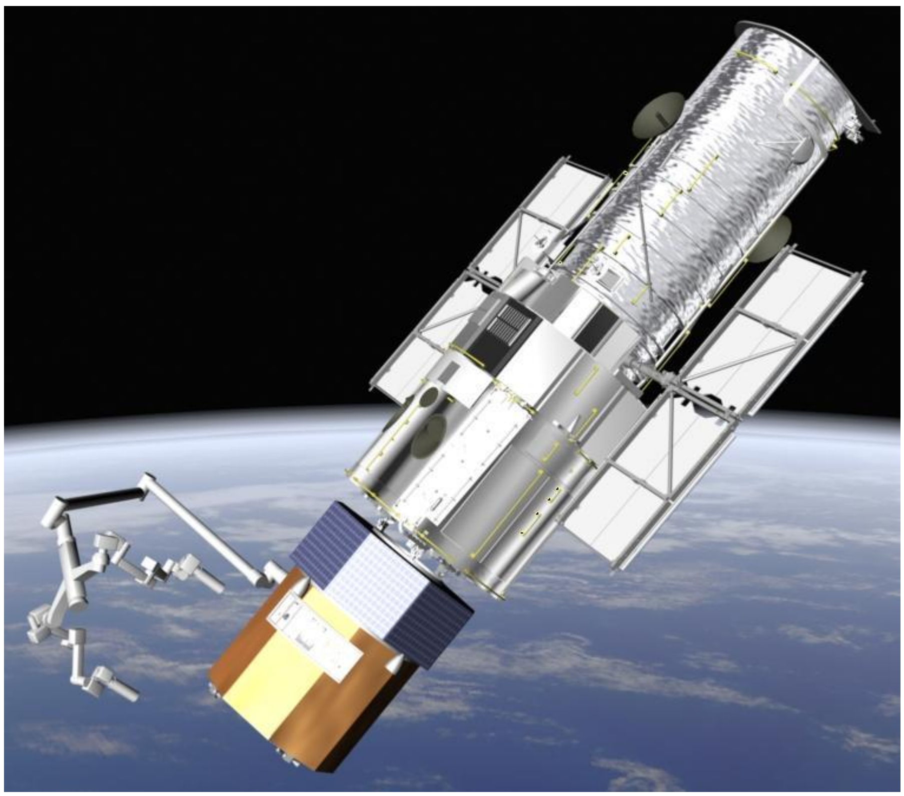

Figure 1-11 Proposed Hubble Robotic Servicing Mission [25,26]

1.1.4 New System Architectures

Another platform that shares the most common characteristics with satellites are airplanes here on Earth. After World War II air superiority was determined to be critical to United States strategic interests and experienced some of the most significant investment during the Cold War. An article in Air Force magazine stated, “Air superiority is the single most important factor in deciding the outcome of modern conventional war [27].” The range of aircraft are limited to the consumable fuel on-board. With the requirements of long-range missions and flying through contested areas the need for aerial re-fueling through air tankers is crucially important for the US Air Force’s strategic mission. An example of aerial refueling is below in Figure 1-12 of an SR-71 Blackbird which was a long-range reconnaissance aircraft.

Figure 1-12 Aerial refueling of an SR-71 Blackbird [28]

Without aerial refueling these long-range aircraft could not have achieved their mission. Aerial tankers enable exponentially more flexible options for aircraft operators as they no longer need to land and recover the aircraft to execute refueling. This issue currently exists for satellites in orbit as they are extremely limited in their options for maneuvering.

This is particularly important for LEO satellites which have a much smaller Field of View (FOV) compared to GEO satellites as shown in Figure 1-3. LEO satellites would benefit more from executing maneuvers to reach more desirable orbits in order to better reach desired ground targets compared to GEO satellites. Since it is much more difficult to maneuver in LEO due to Earth's gravity well, the ability to refuel satellites greatly expands the options for satellites.

One of these concepts for maneuvering in an efficient manner in LEO by using environmental effects is a method called Reconfigurable Satellites (ReCon). ReCon leverages the J2 perturbation caused by Earth's oblateness in order to cause nodal drift of the satellite using less Δv than a traditional direct burn [29]. This allows a system of satellites the ability to enter more persistent ground tracks over targets of interest using less propellant. This is depicted below in Figure 1-13 where satellites are spread out in in a GOM configuration and execute a Δv maneuver to change their RAAN to allow for more repeat ground tracks over particular targets of interest depicted with the yellow star.

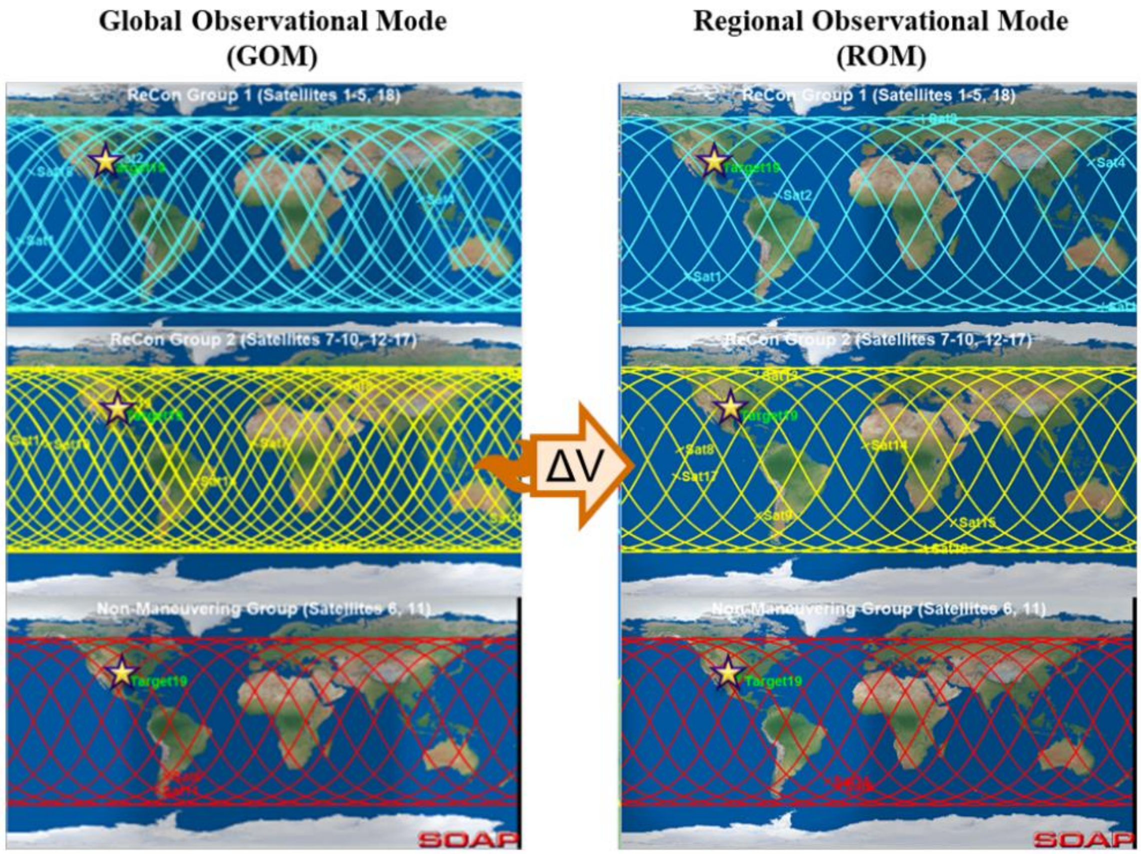

Figure 1-13 ReCon ground tracks between GOM and ROM [30]

However, this ReCon system architecture is limited by the finite Δv that each satellite has in order to execute the maneuver into ROM. This results in limitations for satellite operators to determine the importance and urgency for exercising this capability. It results in a prudent and limited capability due to the reservations of saving this capability for future exigent circumstances or natural disasters. While ReCon shows more utility over conventionally static remote sensing constellations, we can see below in Figure 1-14 that satellites did not reconfigure for targets 1,4,6,8,12,15,16, and 18. P_E/P_{max} is the normalized performance metric analyzing the quality of the reconfigured ground track vs. an idealized one. OOS eliminates the need for decision making and the possibility for underutilization for the ReCon constellation by allowing it maximize utility and manage future uncertainty. As any ReCon constellation that is deployed will be built to future projections and inflexible to changes in demands or requirements. This can enable smaller and scalable ReCon constellations with even greater performance and utility at lower costs.

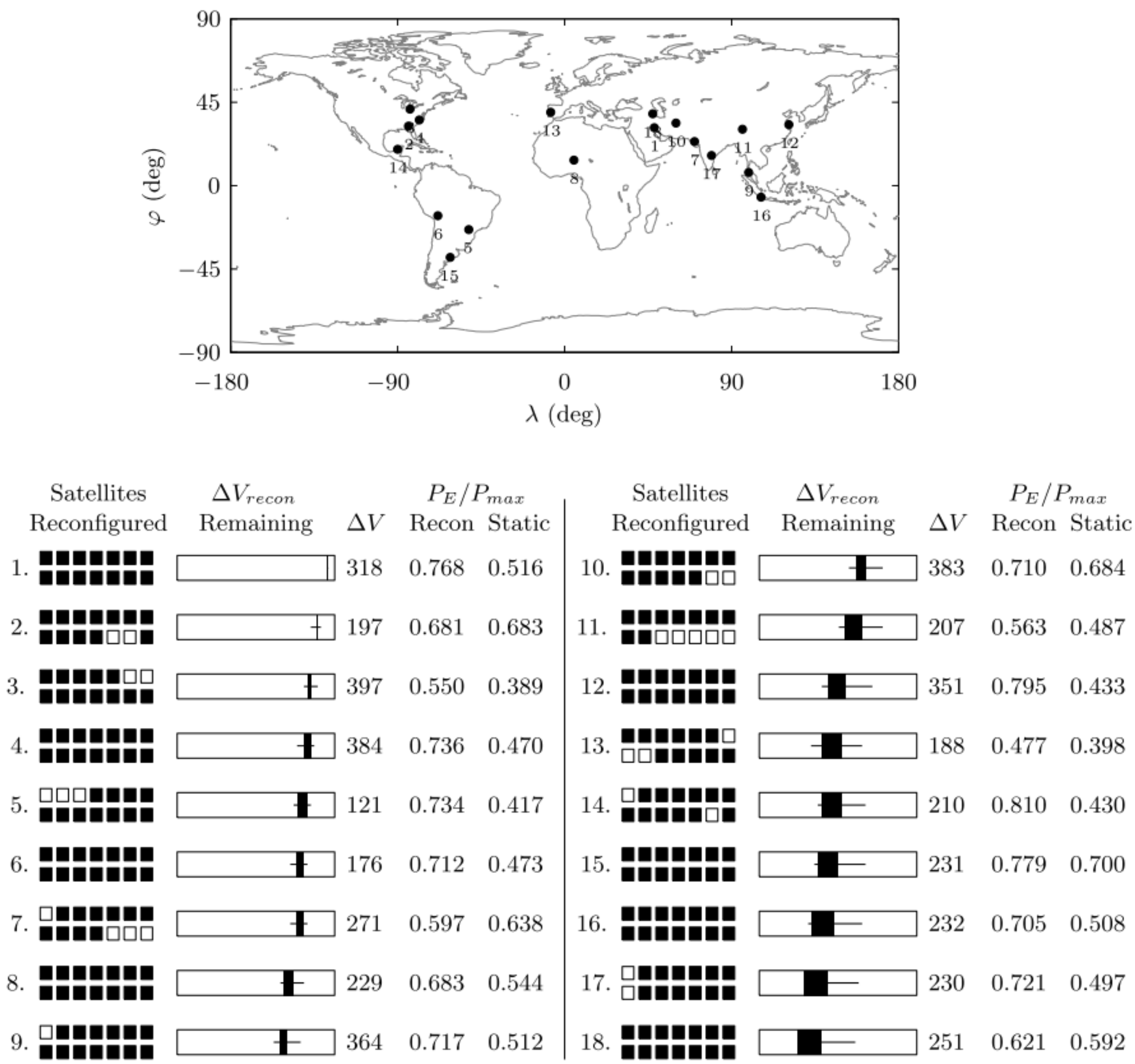

Figure 1-14 Example ReCon use case showing how many satellites were reconfigured for 18 randomized global events of interest [29]

1.2 Cost

Space is hard. As a result, the costs of satellites, space craft, and space systems are some of the most expensive objects that humankind has ever created. The international space station is the most expensive object ever built at approximately $160 billion dollars as of 2010 [31]. Despite the risks to STS-61 and the Hubble servicing mission, they were determined to be worthwhile due to the initial investment of $5.7 billion by the time of launch of Hubble [32]. Most space activity up until most recently has been undertaken by governments who exercised inelastic demand to achieve their strategic objectives or provide for national defense. However, with the growth of commercial space opportunities the desire to drive down operational and overall system costs to achieve sustainable revenues and business models is a requirement for future space system architectures.

1.2.1 Design Life

The initial design of many complex systems begins with it being expensive, unreliable, exotic, unserviceable, and are short in lifespan. As a system or product matures, reliability increases and serviceability becomes critical to mitigating failures and achieving continued revenue or utility. Below in Figure 1-15 we see the "Bathtub Curve" which shows some of the considerations for the lifetime of a product or system.

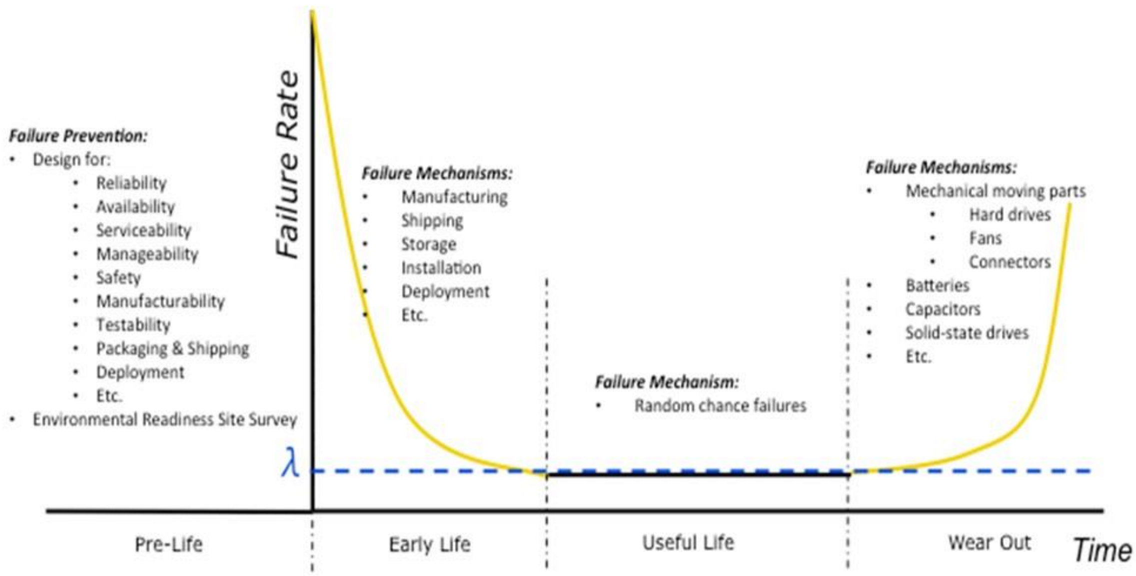

Figure 1-15 Failure rate over time of a system or a product, “Bathtub Curve” [33]

The objective of OOS in relation to the “Bathtub Curve” will be to extend the useful life period and decrease the steepness of the overall system wear out. The steepness of the overall system “Wear Out” is related to the combinatorial effects of multiple components failing making the system inoperable.

The CORONA program was the first operational reconnaissance satellite ever developed and was run by United States government from the late 1956-1972. The first 12 satellites were failures, in total 145 satellites were launched at a cost of $5.4 billion [34,35]. These satellites had extremely short lives due to the limited knowledge of space systems and their limited resources. CORONA satellites relied on a camera film system which was finite in capacity, this resulted in requiring replacement satellites to be built and launched in order to sustain photographic satellite reconnaissance from space. In Figure 1-16 we can see the film supply at the bottom and the two recovery vehicles at the top of the satellite.

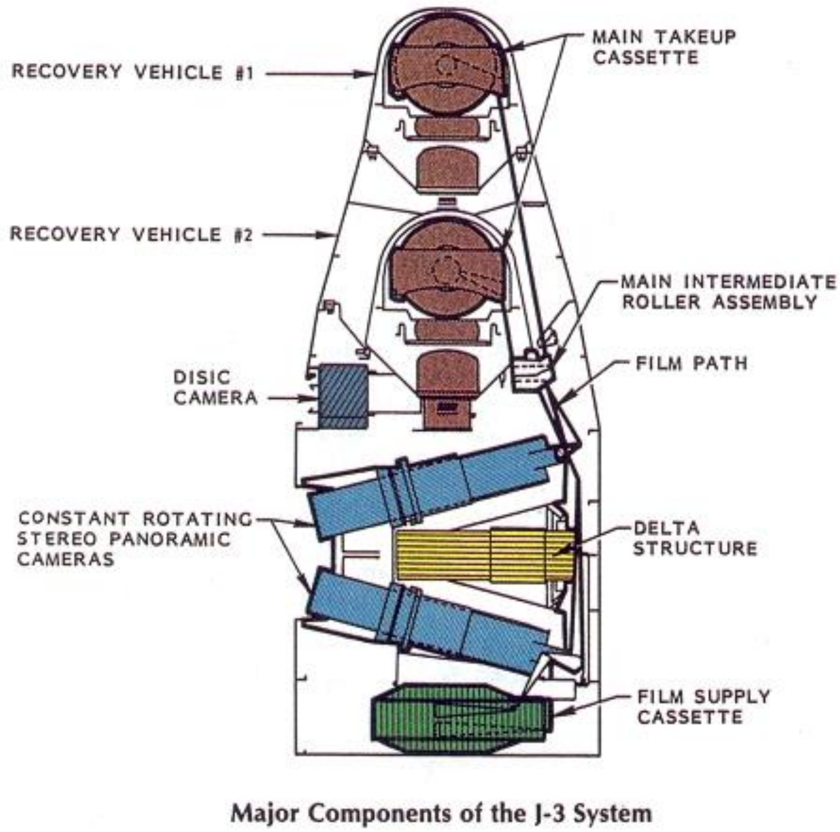

Figure 1-16 CORONA satellite system components [36]

As with any new technology from trains, cars, computers, to planes; each of these systems started with very low serviceability and were highly bespoke. But as time went on their reliability and capabilities greatly increased in conjunction with their serviceability. The B-52 Stratofortress program started in 1945 with its first flight in 1952, planes of the era were expected to last only 15-20 years. However, the plane is currently still flying with plans for them to continue into the 2040s even though the last B-52s ever produced were made in 1963 [37]. This high design life and utility is attributable to the serviceability of the aircraft. The B-52 has been able to far exceed its initial design life by being serviced and upgraded as each component or subsystem was modernized. We can see the old analog technology of the original B-52 cockpit in Figure 1-17 compared to the modern and most recent cockpit in Figure 1-18

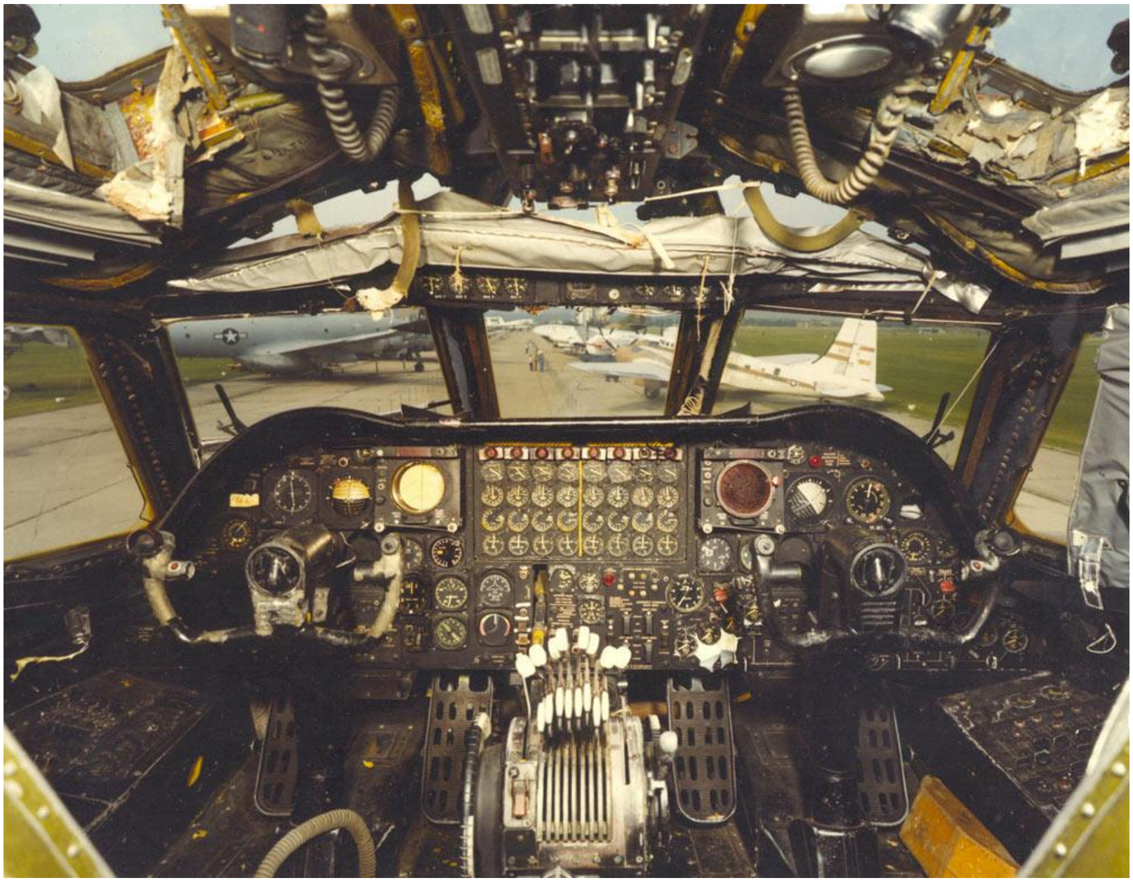

Figure 1-17 B-52 Stratofortress cockpit from the 1960s [38]

Figure 1-18 B-52 Stratofortress cockpit upgraded in 2014 [39]

Virtually every engineered system and product has some sort of periodic or regular maintenance schedule. Our vehicles have set maintenance schedules to replace engine lubrication oil, coolant fluid, mechanical brakes, and more. Airplanes have significant periodic inspection and maintenance intervals to ensure their continued service and longevity. An example maintenance schedule is provided below in Figure 1-19. If it were not for periodic and preventative maintenance vehicles would not last nearly as long as they do now. Satellites are some of the only systems to be self-contained with no maintenance capabilities and to be single use.

Applies for 2014 - 2018			Universal Nissan Recommended Maintenance Intervals for your Nissan											
			5,000	10,000	15,000	20,000	25,000	30,000	35,000	40,000	45,000	50,000	55,000	60,000
Inspect / Test battery and print out test tape.		FREE	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Check all fluids, fill washer solvent.		FREE	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Inspect Windshield Wiper Blades		FREE	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Check for open recalls		FREE	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Replace engine oil and filter conventional	NLOF	$39.95	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Replace engine oil and filter synthetic	NLOFSS	$54.95	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Replace engine oil and filter 5W30 Mobil 1	NLOFS1	$69.95	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Check for any fluid leaks, drive shaft boots		FREE	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Check all exterior lighting		FREE	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Inspect belts for fraying, excessive cracks		FREE	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Inspect / measure tread, adjust pressure & rotate	NROT	$19.95	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Inspect Brake pads, rotors, parking brake , drums & linings.		FREE	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
Replace a/c In-cabin microfilter	CABIN	$59.95			◊			◊			◊			◊
Replace engine air cleaner filter	AF	$39.99						◊						◊
Brake fluid Exchange	BGCF	$119.95				◊				◊				◊
Ala Carte Items - not included in Total Price														
Induction Service (Dealer Recommended)	BGIND	$133.95						◊						◊
Wheel Balance (Dealer Recommended)	NRBAL	$44.95			◊			◊			◊			◊
Four Wheel Alignment (Dealer Recommended)	NAL4	$129.95			◊		◊		◊		◊		◊	
Throttle Body Service (Dealer Recommended)	BGTBS	$89.95			◊			◊			◊			◊
Automatic transmission service (non-CVT)	BGTF	$199.95						◊						◊
CVT transmission service		$219.27												◊
Replace Differential oil* (frontier/xterra/titan/armada)	BGDIFF	$99.95						◊						◊
Replace Radiator cap		$29.95						◊						◊
Conventional Oil price's, Starting at			$59.90	$59.90	$119.85	$169.85	$59.90	$159.80	$59.90	$169.85	$119.85	$59.90	$59.90	$269.75
Synthetic Oil Price's, Starting at			$74.90	$74.90	$134.85	$184.85	$74.90	$174.80	$74.90	$184.85	$134.85	$74.90	$74.90	$284.75
Mobil 1 Oil Price's, Starting at			$89.90	$89.90	$149.85	$199.85	$89.90	$189.80	$89.90	$199.85	$149.85	$89.90	$89.90	$299.75

◊ Signifies various Power Train Variants, not included in total price

* Premium Maintenance based on extreme climate condition due to temperature and elevation.

Figure 1-19 Example of periodic and preventative maintenance service schedule for Nissan vehicles [40]

1.2.2 Mission Assurance

Satellite technology has greatly advanced since the 1970s and we now have satellites deployed in GEO which last upwards of 15 years [41]. The failures of satellites over the last several decades have informed satellite designers and manufacturers on how to build more robust and resilient systems. We now have a variety of system requirements and validation tools which is manifested in ensuring satellite reliability throughout its design life, this is also referred to as mission assurance.

While satellite operators have greatly increased the design life of satellites through increased mission assurance requirements, this has also greatly increased the cost of satellites. A majority of the mission assurance requirements are due to the space launch environment which is where the satellite will experience most of the harshest conditions particularly related to shock, vibration, and thermal. Even though these conditions are only experienced for a short period the satellite must be engineered with excess margins above the minimum threshold of survival in order to ensure successful future operation of the satellite due to the current lack of availability of servicing the satellite after launch.

Uncertainty of future events also influence the design requirements of satellites. Orbital debris impacts, collision avoidance maneuvers, ionizing radiation, and solar events can have detrimental or even catastrophic effects on a satellite. For these environmental reasons satellites must also have additional margin within their systems in dealing with uncertainty in possible future events. Mission assurance testing alone is estimated to cost up to 10% of an entire program's budget by the National Reconnaissance Office but numbers range widely and are incomplete [42]. This does not even consider the amount of over engineering or margin required for systems which also add significant costs.

For all of these reasons OOS is particularly relevant in its ability to reduce or offset mission assurance requirements. By changing the paradigm of viewing satellites as static or frozen in resources and configuration, new opportunities are presented through servicing satellites after deployment to orbit.

1.2.3 Comparative Alternatives

In order to determine the value and utility of OOS we must compare it to alternative options. Since we currently do not use OOS as a methodology for existing satellite systems, we will compare OOS against the current strategies which are used to mitigate on-orbit satellite failures. The comparative alternatives to OOS are:

1. Ground spare – Extra satellites which are built when an initial satellite is built and stored on earth for a possible future launch to orbit in order to replace a malfunctioning or failed satellite. This is also can be referred to responsive launch.

2. Parking orbital spare – Additional satellites which are deployed to an alternative orbital plane as an operational satellite which does not contribute capabilities to the operational satellite constellation. This allows them to process in a different period around earth presenting passive opportunities to replace a malfunctioning satellite at various orbital parameters.
3. Operational orbital spare – Additional satellites deployed to the operational orbital plane but do not constitute the minimum capabilities of the constellation. These satellites are providing excess capabilities above the minimum system requirements and increase resiliency of the operational constellation.

1.3 Thesis Overview

This thesis develops the framework and tradespace for creating generalized solutions and evaluating OOS design sensitivities and client satellite dependencies. The intent is to evaluate the cost benefit analysis for developing an OOS system architecture for pLEO constellations. The numerous variables and attributes to an OOS system architecture will be systematically unified into a combined utility function to determine its performance and weighted against the cost. Comparative alternatives will also be evaluated to populate a tradespace to inform potential decisions concerning the development of an OOS for pLEO.

This thesis follows the following format:

Chapter 2 provides a literature review for pLEO constellations, both existing and planned. It also reviews OOS enabling technologies that have been achieved up until now as well as upcoming OOS programs.

Chapter 3 compares the sensitivity of certain design parameters for an OOS and determines what is feasible. The considerations for sizing, orbital maneuvers, environmental effects, and propulsion are evaluated.

Chapter 4 includes the CONOPs, assumptions, and general overview of what an OOS system architecture would look like in pLEO. It explores using a scalable pod deployment concept. It also covers the compilation of the multi-attribute utility (MAU) function, which evaluates the performance of the tradespace.

Chapter 5 presents the result of the tradespace and evaluates various OOS designs by varying their design inputs against the comparative alternatives of using orbital spares. The performance is compared and evaluated by multiple scenarios in which a client or OOS operator would be either concerned about timeliness, servicing events, servicing mass, or a combination of these factors.

Chapter 6 summarizes the work and recommends future follow-on work.

Chapter

2. Literature Review

2.1 Proliferated LEO

Most satellite constellations that provide near global coverage whether it be communications or global navigation satellite services (GNSS), operate in GEO. But as pLEO becomes an area of focus as discussed in section 1.1.1 in future constellations. We will summarize the developments of pLEO constellations which are fully operational, partially deployed, and planned.

2.1.1 Existing Fully Operational Constellations

Iridium is a telecommunications company that operates a LEO mobile satellite service which consists of 66 satellites operating separated by six orbital planes at an altitude of 781 km and near a polar inclination of 86.4° [43]. These original satellites were built on Lockheed Martin's 700A satellite bus with an eight-year design life. The constellation began deployment in 1997 with the final operational satellites launched in 2002, in total 95 first generation satellites were launched [44]. Iridium is the only fully operational pLEO constellation that provides real-time global coverage for telecommunications which is depicted below in Figure 2-1, we can also see that the six separate orbital planes intersect at the poles which results in a concentration of satellites at the crossing point. The polar orbits were chosen as this symmetrical constellation design was the most efficient way to achieve global coverage. In Figure 2-2 we can see that this decision of polar orbits and clustering resulted in high degrees over overlap for coverage at higher latitudes and much more sparse coverage at the equator where Iridium satellites were at their farthest point from one another.

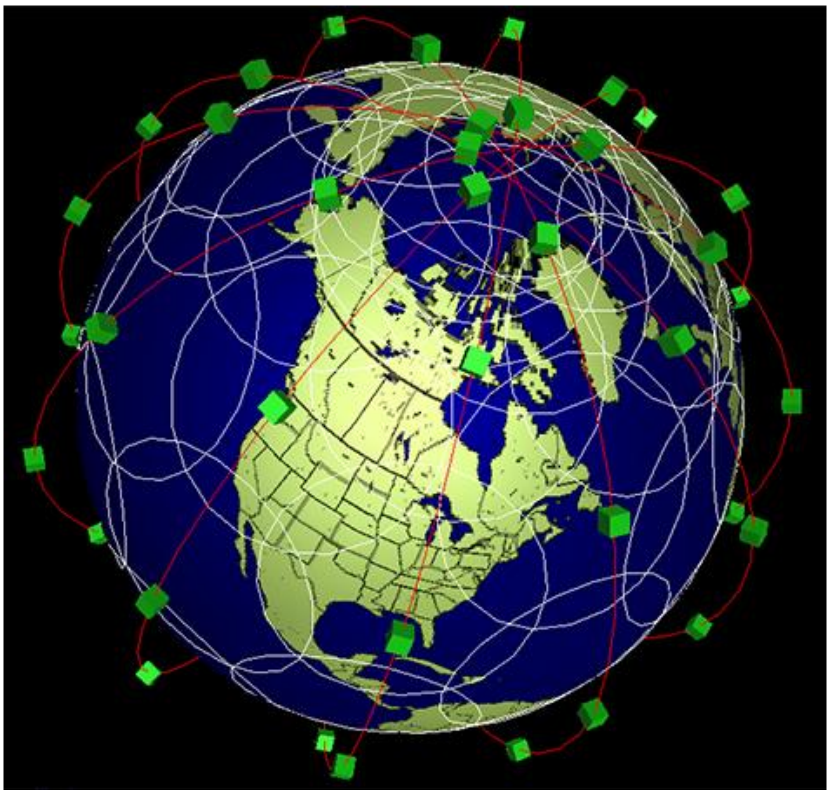

Figure 2-1 Iridium constellation global view [45]

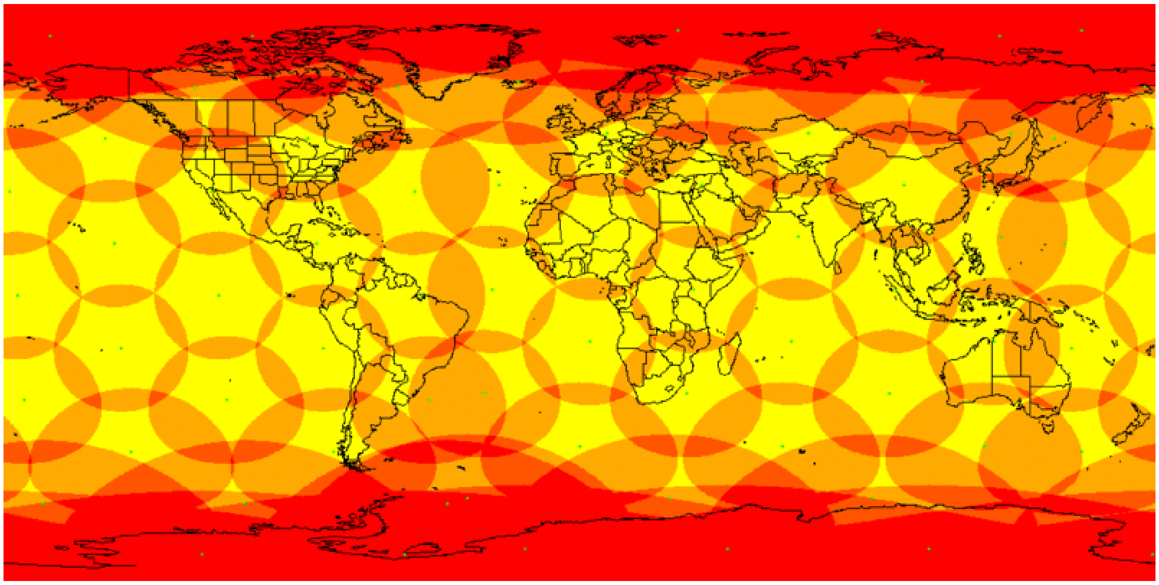

Figure 2-2 Iridium constellation FOV and ground coverage [46]

A single Iridium satellite outage would result in a loss of coverage in locations close to the equator. Many satellites operated beyond their initial eight-year design life. By 2016 two of the core 66 satellites were not operational which resulted in system outages and 80% of the remaining constellation operating without spares, these outages and trend of failures caused concern for Iridium, customers, and the United States Department of Defense [47]. Of the original 95 Iridium satellites launched to orbit 30 were malfunctioning and are not able to be deorbited as of late 2019, they will remain as space debris for at least 100 years [48]. This represents a failure rate of 32%. Not only was Iridium the first LEO constellation that provided global coverage, but the first generation of satellites were successful in lasting far beyond their design life that a second generation of satellites was decided to be deployed in 2007 [49]. The second generation of Iridium's constellation called Iridium-Next were deployed in 2017 with 66 operational and 9 orbital spares completed in 2019 at a cost of $3 billion [49].

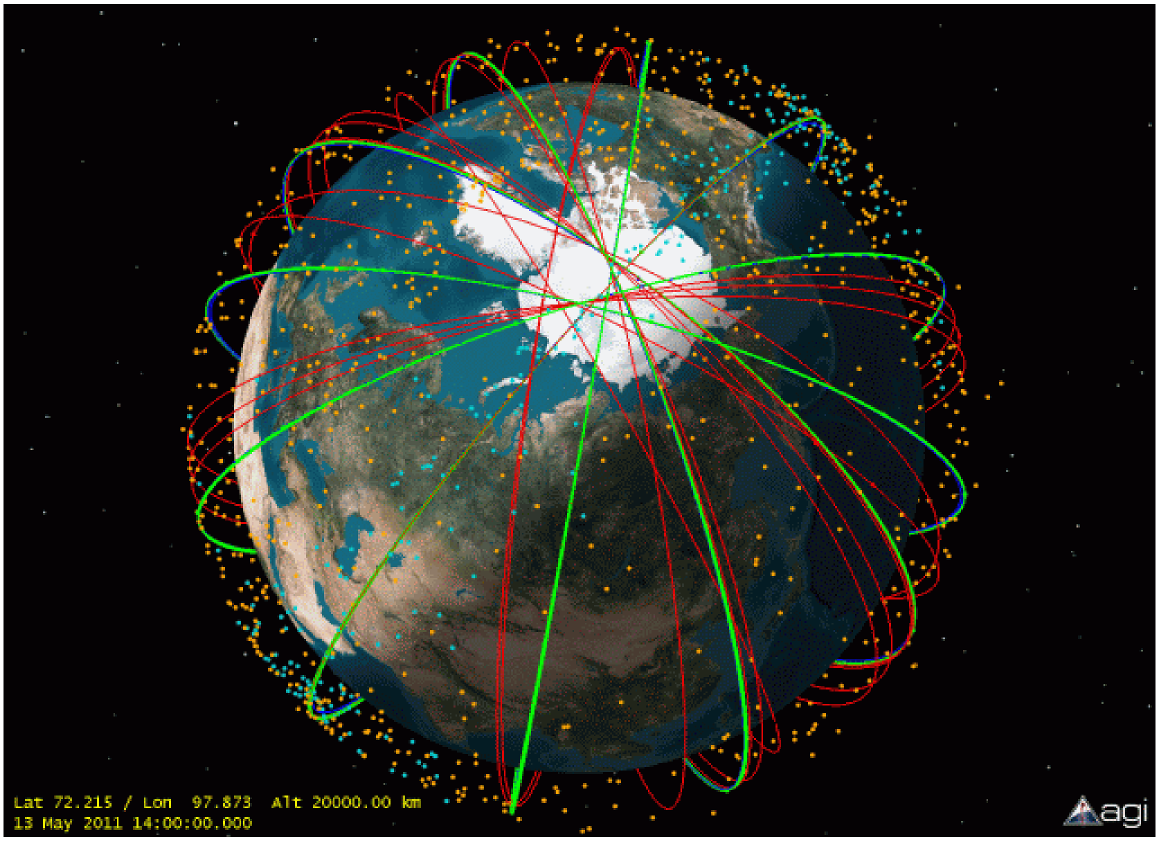

Figure 2-3 Orbital debris from Iridium 33 and Cosmos 2251 collision in 2009 [50]

In 2009 Iridium 33 collided with Kosmos-2251, a defunct Russian military communications satellite, which resulted in the most significant orbital collision of satellites ever and the largest contributor to space debris with approximately 1,000 objects over 10cm being tracked [51]. In Figure 2-3 we can see the orbital debris from the collision with Iridium 33 debris shown in light blue and the Cosmos 2251 debris shown in orange [50]. This has called for increased demands in de-orbiting policy as the situation could have been avoided if Cosmos 2251 were deorbited at the end of its life. Approximately only 30% of operators currently deorbit their satellites in within 25 years of their end of life [52].

2.1.2 Partially Deployed Constellations

There are some constellations that are currently being deployed, tested, and have succeeded in launching enough satellites into orbit to achieve technology demonstrations. But these partially deployed constellations have not yet achieved their fully planned operational capabilities in order to begin sustainable business operations or have achieved reliable or global coverage.

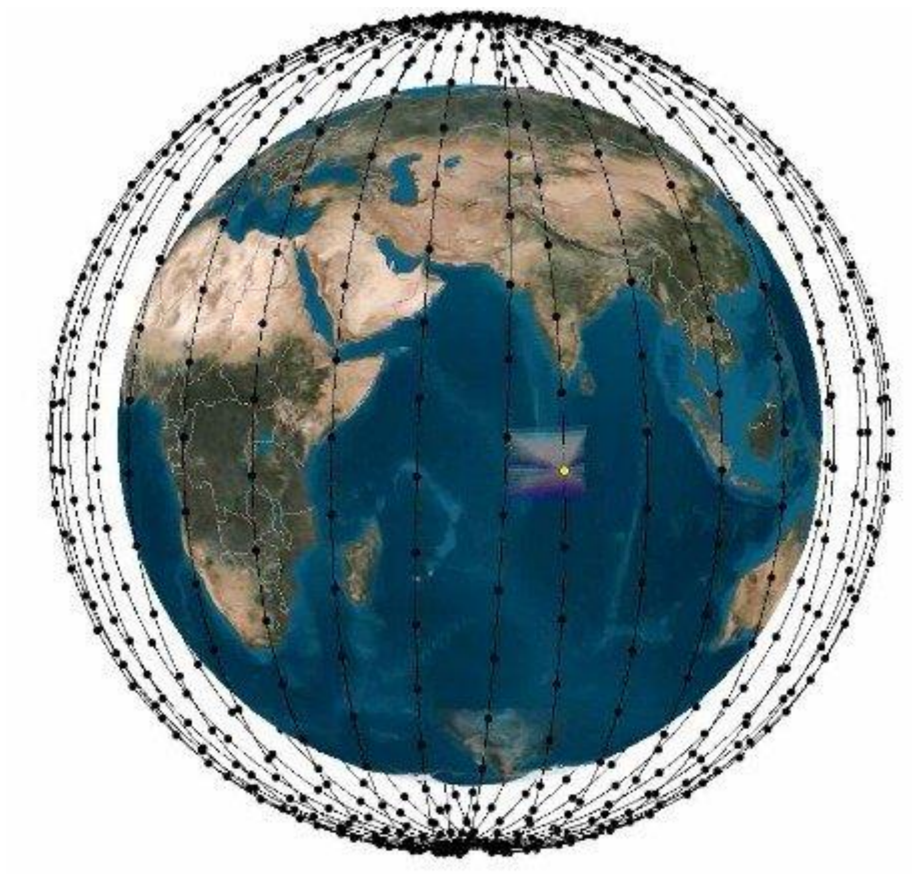

Figure 2-4 OneWeb constellation example [53]

OneWeb

In June 2014 OneWeb, at the time called WorldVu, acquired the spectrum license from a previously planned space based internet satellite system called SkyBridge which failed in 2000 [54]. Google was involved with OneWeb at the beginning but then went on to work with Elon Musk at SpaceX to explore satellite broadband in September 2015 [55]. The initial design of OneWeb consisted of 640 satellites at an altitude of 1,200 km [56,57]. The company went through many announcements and changes to their design while they went through bankruptcy in March 2020, the company was bought by a UK government and Bharti Global in July 2020 [58,59]. The first launch of OneWeb satellites took place February 2019 launching 6 satellites into orbit and as of March, 25th 2021 OneWeb has 146 of the planned 648 in orbit [60]. OneWeb plans to complete the 648 first-generation satellite constellation by 2022 [61]. We can see an example of the OneWeb constellation in Figure 2-4.

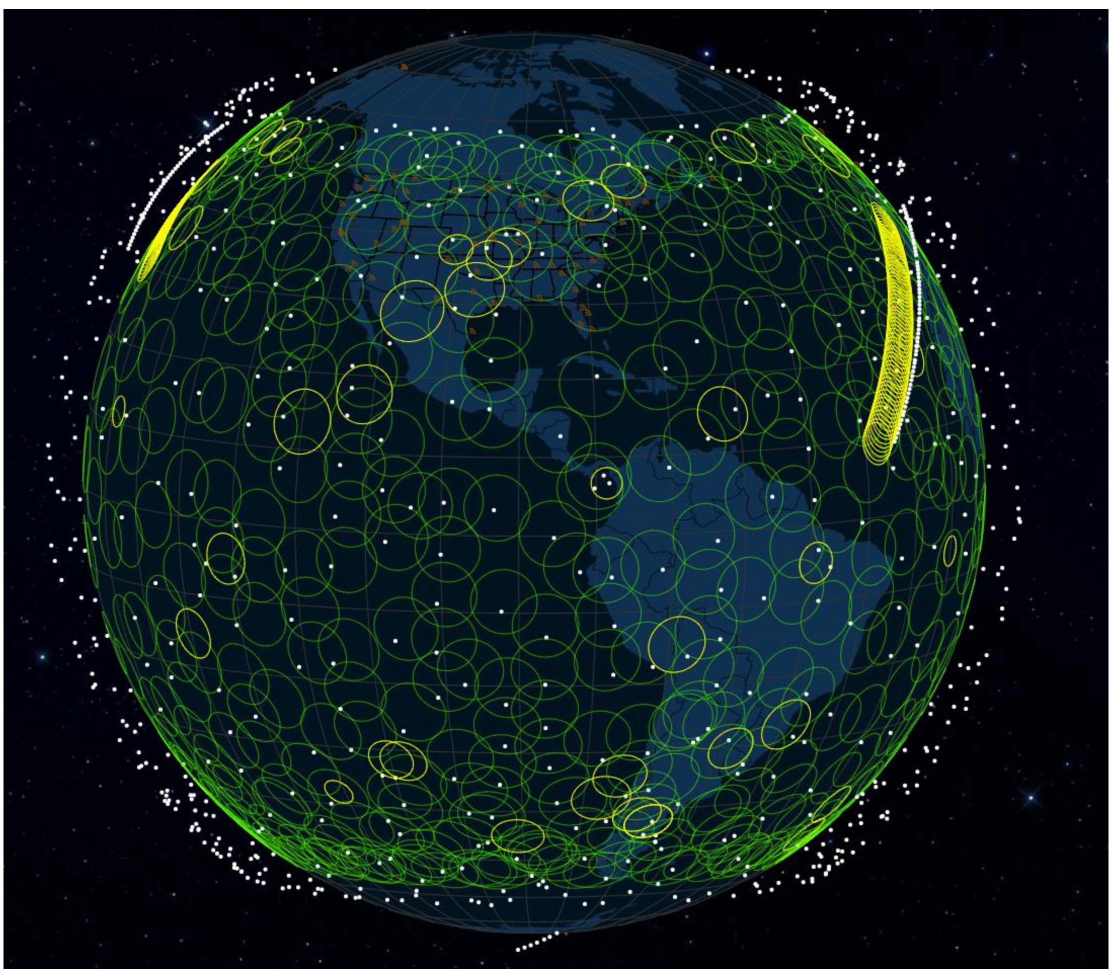

Figure 2-5 Starlink satellites as of April 2021 [62]

Starlink

SpaceX is currently developing and deploying a satellite internet constellation called Starlink. Starlink consists of thousands of mass-produced small-satellites in LEO. The program was announced in January 2015 with Starlink being made of 4,000 satellites to provide high-speed internet across the world [63]. The constellation's primary goals are to transport back-haul long distance internet traffic, a smaller portion of their operations will enable internet service provisions directly to consumers [64]. Starlink did not require or aim to achieve full global coverage and compromised their constellation design to serve a majority of the Earth's population and infrastructure which largely do not extend to extreme latitudes near the Earth's poles.

The initial design of Starlink called for the satellites to orbit at 1,100-1,325 km in a simple homogenous design spread across 83 orbital planes at a ˜53° inclination [65]. However, many of the initial specifications have changed including the number of satellites, altitude, and homogeneity as the constellation will now occupy several altitudes forming multiple shells as SpaceX has filed new Federal Communications Commission (FCC) license requests [66]. Originally Starlink did not propose to provide satellites to cover polar orbits as the original constellation had each plane inclined at 53°, however Starlink's most recent FCC approval permits satellites to occupy near polar orbits at 97.6° for testing purposes [67].

Current coverage of Starlink can be seen in Figure 2-5 where satellites are depicted as white dots and green circles represent the FOV or coverage area of that satellite, we can see that higher altitudes above 70 degrees and lower altitudes below -55 degrees are not covered by the Starlink constellation due to the ˜53°

inclination of the Starlink constellation. Similar to the Iridium constellation in Figure 2-1, there is a concentration of satellites at higher latitudes resulting in larger coverage gaps near the equatorial plane. Constant coverage in Northern and Southern latitudes have been achieved, future Starlink launches will close these coverage gaps near the equator to achieve near global coverage. Starlink's most recent launch on April 7th, 2021 of 40 satellites now brings the total constellation size to 1,378 satellites, SpaceX is now roughly 4-5 launches away from the 28 launches necessary to achieve global coverage [66]. The total cost of Starlink is estimated by SpaceX leaders to be $10 billion dollars [68].

2.1.3 Planned Constellations

Many companies have developed, designed, announced, secured funding, and even received spectrum license approval for their planned satellite internet constellations. These constellations are the ones that have significant resourcing and are anticipated to begin deploying their satellite constellations.

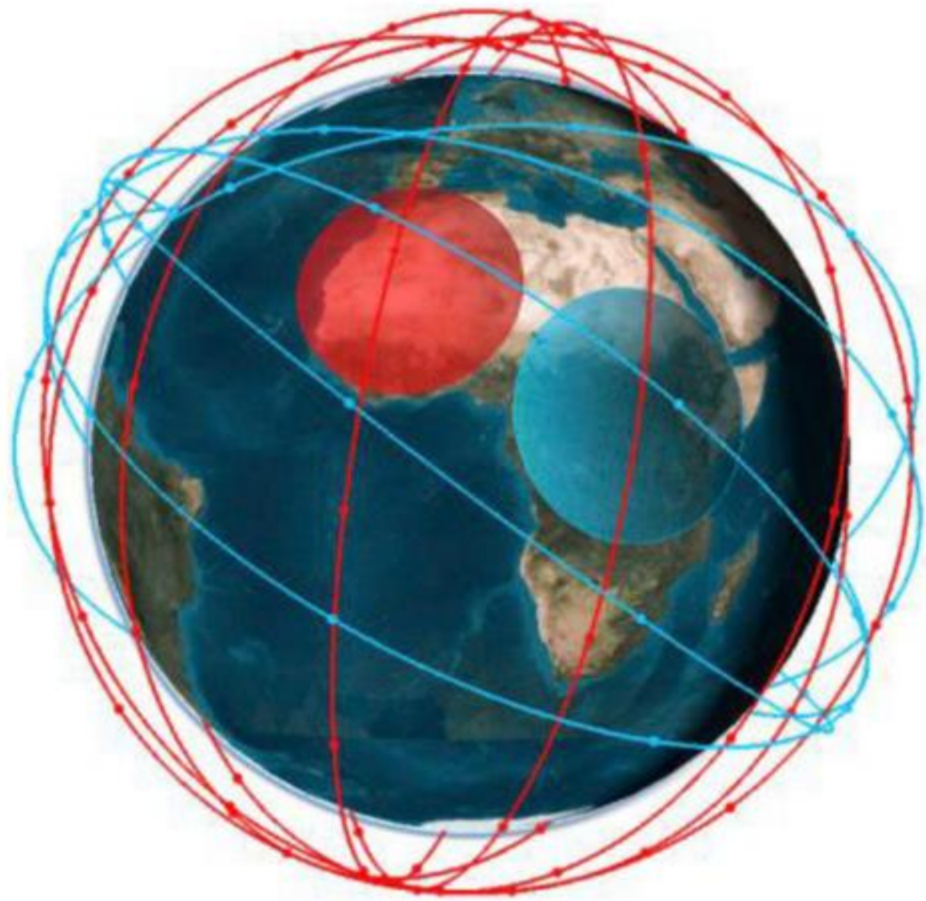

Figure 2-6 Lightspeed constellation example [53]

Lightspeed

Telesat announced in November 2016 that they planned to deploy an internet constellation in LEO with at least 117 satellites in two orbital configurations [69]:

1. Polar Orbits: Six orbital planes each with 12 satellites at an altitude of 1,000 km and an inclination of 99.5 degrees. Red orbits in Figure 2-6.
2. Inclined Orbits: 45 satellites spread over five orbital planes at an altitude of 1,248 km and an inclination of 37.4 degrees. Blue orbits in Figure 2-6.

This new pLEO constellation is called Lightspeed. Telesat launched their phase 1 LEO satellite in January 2018 to conduct ground station testing and development, this satellite has a three year design life and will be phased out for when Lightspeed is planned to deploy in 2022 [70,71]. Lightspeed is under consideration to expand up to 298 satellites and 20 inclined planes, however Telesat has not yet received updated licensing approval [72,73].

Kuiper

Amazon has plans to deploy a pLEO constellation to provide space based internet capabilities called Kuiper, which received approval from the FCC in 2019 to launch 3,236 satellites in 98 orbital planes with an altitudes of 590 km, 610 km, and 630 km [74]. Amazon has said it will invest $10 billion in Kuiper, further details on the Kuiper constellation are sparse [75].

Blackjack

The Defense Research Projects Agency (DARPA) in partnership with the Space Development Agency (SDA) has invested in a program called Blackjack to explore leveraging global highspeed broadband internet services for the U.S. Department of Defense as an alternative to GEO satellites [76]. SDA is going on to develop and demonstrate new space architectures in LEO as a lower cost alternative to more exquisite GEO satellite systems which are currently widely used [77].

2.1.4 Summary of pLEO Constellations

		Telesat	OneWeb	SpaceX	
Results for max. system throughput	Num. satellites	117	720	4425	–
	Max. total system throughput	2.66	1.56	23.7	Tbps
	Num. ground locations for max. throughput	42	71	123	–
	Num. gateway antennas for max throughput	221	725	~3500	–
	Required number of gateways per ground station	5–6	11	30	–
	Average data-rate per satellite (real)	22.74	2.17	5.36	Gbps
	Max. data-rate per satellite	38.68	9.97	21.36	Gbps
	Satellite efficiency	58.8	21.7	25.1	%
Scenario with 50 ground stations					
Results with 50 GS	Capacity with 50 GS	2.66	1.47	16.8	Tbps
	Number of gateway antennas required	221	525	1500	–
	Average data-rate per satellite (real)	22.74	2.04	3.72	Gbps
	Max. data-rate per satellite	38.68	9.97	21.36	Gbps
	Satellite efficiency	58.8	20.5	17.4	%

Table 2-1 Summary of constellation performance [53]

Iridium works on L-band and does not provide the bandwidth that future pLEO constellations are aiming to provide. Currently Kuiper's details are limited and not available for comparison. Previous analysis of system performance of Telesat, OneWeb, and SpaceX's pLEO constellations are in Table 2-1, max total system throughput was 2.66 Tbps, 1.56 Tbps, and 23.7 Tbps for Telesat, OneWeb, and SpaceX respectively [53]. Satellite efficiency is the ratio between achieved average data-rate per satellite and its maximum data-rate [53].

2.2 OOS Technology Development

OOS has now become a viable system due to development of previous technologies and space missions. We will review the previous missions and future planned missions that enable OOS as a viable and feasible system.

2.2.1 Previous Operational Missions Enabling OOS

Rendezvous and Proximity Operations (RPO)

Individual satellites were limited in what they could accomplish during space missions, the need for RPO was identified as critical to the US mission to land a human on the moon. The first mission to rendezvous two spacecraft in orbit was Gemini 6 and Gemini 7 in December 1965 where they demonstrated the ability to conduct orbital maneuvers to bring the spacecraft within 0.3 meters of one another [78]. The first docking in space took place in March 1966 when Gemini 8 rendezvoused and docked with a passive target which was the Agena Target Vehicle [79]. The first rendezvous and docking of crewless satellites took place in October 1967 when Cosmos 186 and Cosmos 188 paving the way for complex LEO systems to operate jointly [80].

Space Stations

The limitations of individual space vehicles and the staging resources in orbit was identified early in space programs, space stations were proposed as platforms to expand capabilities of space missions and enable missions to be less constrained by launch volume as well as mass. Space stations also provide the ability to execute experimentation and testing for spaceflight. The first space station to be launched was the Salyut 1 in 1971 which was a monolithic design and self-contained, later in 1986 the Mir space station was launched which was a modular spacecraft as operators saw the need for flexible and adjustable designs [80]. Today the International Space Station (ISS) is the largest human made object in space and has been assembled over many years through many stages and modules since 1998, the first modules launched and docked robotically but all other modules were delivered and installed by the Space Shuttle [80].

<u>Space Shuttle</u>

The Space Shuttle was a crewed space vehicle that was designed to support short crewed missions to support the space station through assembly and ongoing operations, the Space Shuttle was also designed to launch, service, and retrieve satellites [81]. One of the most critical capabilities to support all of the missions of the Space Shuttle was the Shuttle Remote Manipulator System (SRMS) which was also known as "Canadarm" which is a six degree of freedom (DOF) remotely controlled manipulator, the SRMS flew on over 50 missions and enabled servicing missions, satellite deployment, retrieval, EVA astronaut assists, shuttle inspection, and on-orbit assembly [82]. The SRMS was also pre-programmable capable of offering remote or fully autonomous operation.

Service mission	Time	Space Shuttle	Detailed servicing operations
SM1/STS-61	December 1993	Endeavour	• Removed the High Speed Photometers. • Install the COSTAR. • Upgraded WFPC with the WFPC2. • Replaced the solar arrays and their drive electronics. • Replaced four gyroscopes, two magnetometers. • Upgraded the onboard computers with added coprocessors. • Boosted HST's orbit.
SM2/STS-82	February 1997	Discovery	• Removed the Goddard High Resolution Spectrograph (GHRS) and Faint Object Spectrograph (FOS). • Installed the Space Telescope Imaging Spectrograph (STIS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). • Replaced an Engineering and Science Tape Recorder with a new Solid State Recorder. • Repaired thermal insulation.
SM3A/STS-103	December 1999	Discovery	• Replaced all six gyroscopes. • Replaced a Fine Guidance Sensor (FGS) and the computer. • Installed a Voltage/temperature Improvement Kit (VIK). • Replaced thermal insulation blankets.
SM3B/STS-109	February 2002	Columbia	• Replaced the FOC by the Advanced Camera for Surveys (ACS). • Revived the NICMOS by installing a closed-cycle cooler. • Replaced the solar arrays.
SM4/STS-125	May 2009 (Initially planned to conduct in 2003 and then delayed due to Columbia's accident.)	Atlantis	• Installed the replacement data-handling unit. • Repaired the ACS and STIS systems. • Installed improved nickel hydrogen batteries. • Installed two new observation instruments including Wide Field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS). • Installed the Soft Capture and Rendezvous System.

Table 2-2 Space Shuttle missions to service HST [83]

The Space Shuttle was most well-known for servicing the Hubble Space Telescope (HST) across five missions from 1993-2009 correcting initial deployment errors as well as upgrading HST's components and performance [84]. Details for the HST servicing missions can be seen in Table 2-2. The Space Shuttle also went on to retrieve and service several satellites listed in Table 2-3. STS-41-C's repair of Solar Max was the first orbiting satellite to be repaired in space, this demonstrated that a satellites life could be extended with direct intervention of a servicing mission [85]. The Space Shuttle validated the possibility of servicing satellites to extend utility and satellite lives.

Service Mission	**Date**	**Space Shuttle**	**Service**
STS-41-C (STS-13)	April 1984	Challenger	Repair of Solar Max satellite attitude control module and instrument payload replaced in orbit [85]

STS-51-A (STS-19)	November 1984	Discovery	Recover Palapa B2 and Westar 6 satellites due to previous failed deployment [86]
STS-49	May 1992	Endeavour	Serviced perigee kick motor for Intelsat VI and redeployed [87]

Table 2-3 Space Shuttle satellite servicing missions

XSS-10

The Air Force Research Laboratory (AFRL) developed a class of microsatellites called Experimental Small Satellite (XSS) to explore topics related to inspection and RPO. XSS-10 was a 36 kg satellite which was a technology demonstration mission for autonomous line of sight navigation and autonomous inspection which was successfully flown in January 2003 [88]. XSS-11 was a follow-on mission of a larger 100 kg satellite which successfully conducted autonomous RPO operations in April 2005 [89].

Orbital Express

DARPA launched the program Orbital Express in March 2007 which successfully demonstrated the utility and technical feasibility of a fully autonomous robotic OOS system [90]. Orbital Express consisted of two satellites, the servicer autonomous space transfer and robotic orbiter (ASTRO) and the target satellite next generation satellite/commodity spacecraft (NextSat/CSC) [91]. Over the course of three months ASTRO successfully executed RPO, station keeping, target capture, docking, propellant transfer, battery replacement, and flight computer replacement on the NextSat target vehicle [91]. Orbital Express was an extremely successful program and demonstrated that the technological barriers for OOS were surmountable.

Mission Extension Vehicle

Northrop Grumman has achieved the most recent major OOS milestone in successfully docking with a client satellite in order to provide station keeping services for two satellites in GEO through the Mission Extension Vehicle (MEV) programs, this is the first commercial OOS mission that provides mission lifetime extension before relocating the client satellite into a graveyard orbit [92]. Intelsat 901's originally was built with a 13 year design and launched in 2001 [93].

MEV-1 launched in March 2019 and successfully docked with Intelsat 901 in April 2020 where it will provide five years of mission life extension, this enables Intelsat to operate their satellite into 2025 which nearly doubles the initial design life [94]. In April 2021 MEV-2 successfully docked with Intelsat 10-02 which has been in operation since 2004, this OOS will also provide five years of mission extension before retiring the satellite to a graveyard orbit [95]. Both Intelsat satellites were limited by their amount of propellant to achieve station keeping in their operational orbits, after completion of their initial missions both MEVs will move to service other satellites [95]. MEV utilizes a nozzle which inserts into apogee kick motor of the target satellite and the adapter ring to grasp the target satellite, while this system was specific to this mission and their targets the question and concern about commonality of OOS interface has been broached by many potential OOS operators as well as clients [96].

2.2.2 Future OOS Missions

Astroscale

Astroscale is a private startup company that aims to provide end of life and deorbiting services to other satellite operators, End-of-Life Services by Astroscale demonstration (ELSA-d) mission was launched in March 2021 [97]. ELSA-d plans to inspect, rendezvous, magnetically dock, and capture a target satellite in LEO, ELSA-d also plans to execute these missions as the target satellite is not-tumbling, tumbling, and also from far range [98].

The company also announced a second program called Active Debris Removal by Astroscale (ADRAS) which came from their selection by the JAXA Commercial Removal of Debris Demonstration Project (CRD2). CRD2 is a program that plans to execute the first deorbit of a large debris object which will be a spent JAXA rocket body, this demonstration mission will take place sometime around 2022 [99].

Lockheed Martin GPS Block III

In 2018 Lockheed Martin was awarded a contract to build up to 22 of the third generation of GPS satellites otherwise known as Block 3 [100]. In December 2020 Lockheed Martin was awarded an additional contract to build the 11th and 12th, GPS Block 3F satellites [100]. Unlike the previous Block 3A satellites, Block 3F will be deployed with OOS hardware in mind to enable future interfaces and upgrade capability with future launches planned in 2022 [101].

Kurs Orbital

A Ukrainian startup company called Kurs plans to build and launch an OOS vehicle, their company leverages OOS RPO and docking technology developed under the former Soviet Union which was used for the Mir space station [102]. This Kurs plans to upgrade this legacy system with more recent advancements made in machine vision, radar, and robotics to execute autonomous operations [102]. While the initial technology demonstration is slated for 2023 the company plans to build four OOS vehicles to offer relocation and deorbiting services by 2025 [102].

RSGS

DARPA has a program called Robotic Servicing of Geosynchronous Satellites (RSGS), RSGS' objectives are to demonstrate the robotic capabilities of an OOS in GEO to include high-resolution inspection, anomaly correction, cooperative relocation, and upgrade installation [103]. DARPA has teamed with Space Logistics LLC, a subsidiary of Northrop Grumman, which also operates the MEV program [104]. RSGS is slated to launch in 2023 with servicing of government satellites at a set price and the ability for follow-on commercial opportunities [104].

OSAM-1

NASA has identified a new national initiative for the US space program called On-Orbit Servicing, Assembly and Manufacturing (OSAM), this initiative it supported by two technology demonstration programs called OSAM-1 (formerly called Restore-L) and OSAM-2 [105]. OSAM-1 is scheduled for launch in 2024 where it will first refuel Landsat 7 and then conduct on-orbit assembly demonstration of a communications antenna using Space Infrastructure Dexterous Robot (SPIDER) [106]. SPIDER is a robotic arm being developed by Maxar in a public-private partnership with NASA, SPIDER was originally called Dragonfly but was renamed as when it became part of the OSAM-1 mission [107,108].

OSAM-2, formerly known as Archinaut One, is a technology demonstration mission to deploy a solar array in space [105]. The mission leverages additive manufacturing and 3D printing of large beams to deploy larger solar arrays than would otherwise be possible under traditional solar array deployment configurations [109].

Future of OOS Summary

The future of OOS looks promising with the current amount of interest and initiatives for technology demonstration missions. Combined with the private-public partnerships in programs like RSGS. If the planned demonstration missions have continued success, the possibility of commercially viable OOS looks like it may become a reality.

Chapter

3. OOS System Design Considerations

3.1 Orbital Elements

We must consider the key parameters in designing an OOS system architecture for pLEO. In order to execute OOS the servicer must meet with the client satellite in time and space. The position of an object in space is most commonly described by its the classical orbital elements as depicted in Figure 3-1 and Figure 3-2.

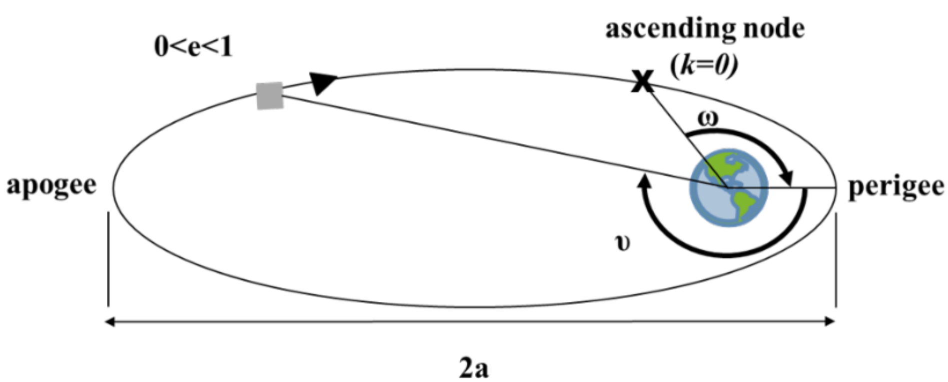

Figure 3-1 Classical orbital elements [30]

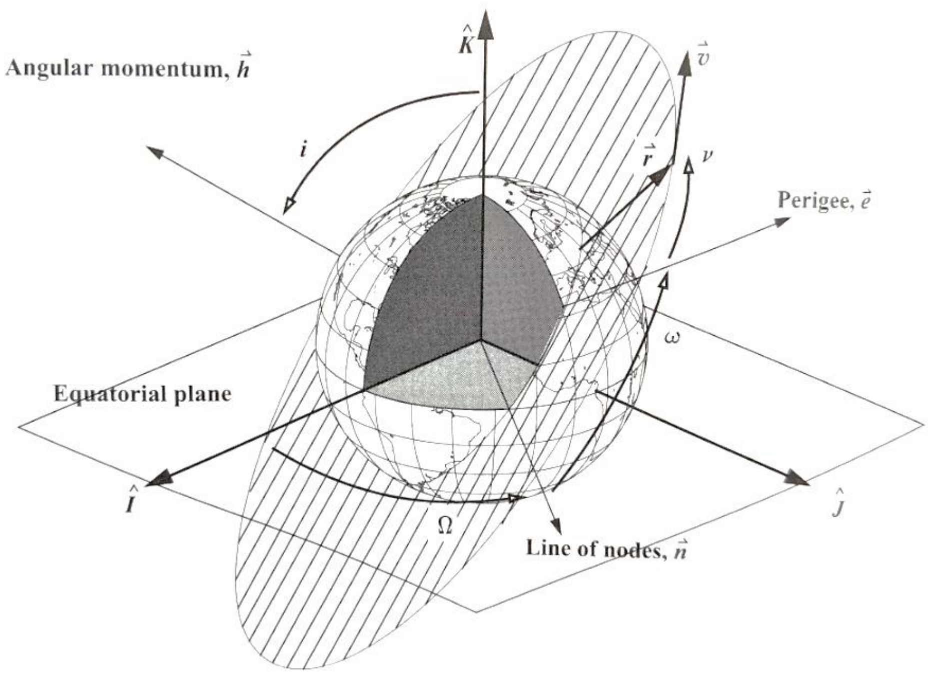

Figure 3-2 Classical orbital elements[110]

A satellite orbit is defined by the orbital elements $a, e, i, \Omega, \omega,$ and v. The semi-major axis, a, is the length of the orbit at its widest point. Eccentricity, e, represents how elliptical the orbit is from 0 (circular) to 1 (elliptic). Inclination, i, is how inclined the orbit is from the equatorial plane. Right-ascension of the ascending node (RAAN), Ω, is the crossing point at which the orbit passes through the equatorial plane. The argument of perigee, ω, is the location of the lowest point of the orbit relative to the ascending node. True anomaly, v, is the location of the satellite in the orbit relative to the perigee of the orbit. We will consider alignment of the orbital elements both by direct impulsive orbital maneuver, leveraging the environmental effects of LEO, and the use of chemical or electric propulsion.

3.2 OOS Sizing and Assumptions

As we seek to create a generalized solution to the OOS we will derive our mass from previous OOS missions in Figure 3-3. Exact figures for OSAM-1 vary, note that Restore-L was the original LEO OOS program which became OSAM-1* that had a wet mass of 4,000 kg [111,112]. Estimates have ranged up to 6,5000 kg as SPIDER was added to the program for a follow-on assembly mission and a deorbiting study was executed by NASA [113]. Propellant mass accounts for ~50% of operational or commercial satellites, we will assume a dry mass of 1,000 kg for the OOS servicer as inert mass will not be carried throughout the mission profile as will be explained in Chapter 4.

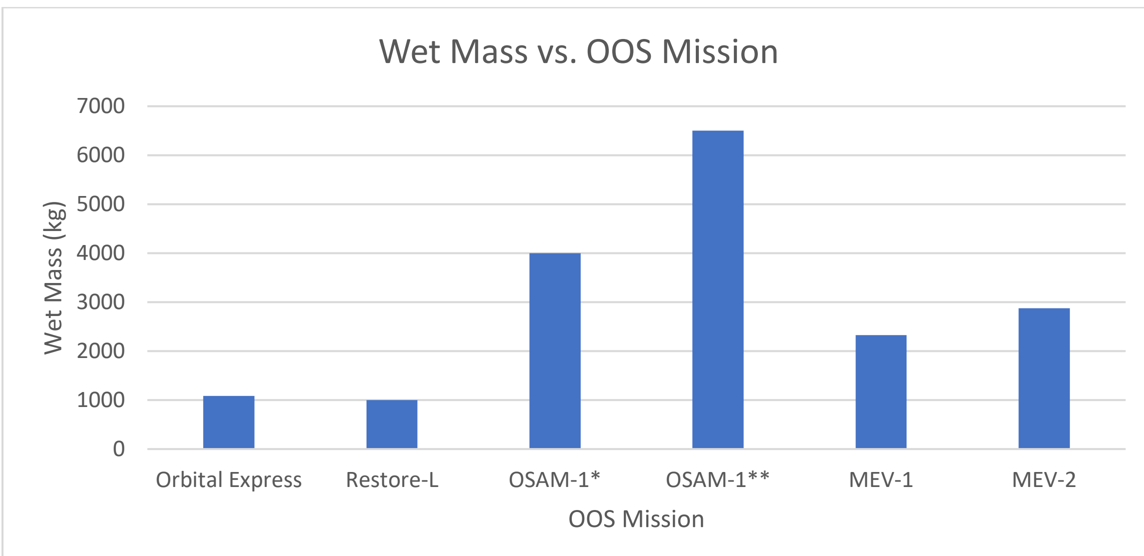

Figure 3-3 Wet Mass vs. relevant OOS missions [111–115]

3.3 Impulsive Orbital Maneuvers

As an OOS moves from one client target to the next we must align the orbital parameters of the OOS to the client target. In this paper we will only consider circular orbits as all pLEO constellations are designed with circular orbits so we will not consider eccentricity, e, as well as argument of perigee, ω.

3.3.1 Inclination/Direct Plane Change (i)

One of the most difficult maneuvers in orbital mechanics is an inclination/direct plane change. Let the change in velocity required to change planes be represented by ΔV_{plane}. This equation is represented below and is a function of the initial orbital velocity, V_{orbit}.

$$V_{orbit} = \sqrt{\frac{\mu}{a}} \qquad 3\text{-}1$$

$$\Delta V_{plane} = 2V_{orbit} \sin\left(\frac{\Delta \mathrm{i}}{2}\right) \qquad 3\text{-}2$$

Since V_{orbit} is a function of the size of the orbit, a, higher altitudes result in lower orbital velocity. Therefore ΔV_{plane} becomes significantly smaller as the size of the orbit increases. This provides significant disadvantages in LEO as the smaller orbit sizes require significantly more ΔV in lower altitudes. This plane change can also be executed at the poles to execute a ΔΩ change, however this maneuver is still cost prohibitive in LEO.

3.3.2 In-Plane Maneuver (a, v)

We can match the a and v of the client satellite using the Hohmann transfer. Let a_0 be the semi-major axis for the client orbit and a_1 be a smaller phasing orbit. The easiest way to align these parameters is by executing a synchronous rendezvous through a Hohmann transfer. The required amount of energy required to execute an in-plane maneuver is provided by the $\Delta V_{Hohmann}$ below.

$$a_{transfer} = a_0 + a_1 \tag{3-3}$$

$$V_0 = \sqrt{2\left|\frac{\mu}{a_0} - \frac{\mu}{2a_{transfer}}\right|},\ V_{transfer1} = \sqrt{2\left|\frac{\mu}{a_1} - \frac{\mu}{2a_{transfer}}\right|} \tag{3-4}$$

$$\Delta V_{Hohmann} = \left|V_0 - V_{transfer0}\right| + \left|V_1 - V_{transfer1}\right| \tag{3-5}$$

We can use $\Delta V_{Hohmann}$ to both change our orbital size to match a. Secondly, we can use the Hohmann transfer to close the difference in true anomaly, Δv by using the difference in orbital periods, T, between the client orbit and the phasing orbit. In order to determine the ΔV_v we must set the altitude, a_1, of the phasing orbit. N represents the number of orbits that the OOS servicer must stay in the phasing orbit in order to close the Δv. One constraint that is imposed is that the Hohmann transfer orbit cannot have a perigee, $r_{transfer\_peri}$, that is lower than 200km due to orbital drag. We must execute one impulsive burn, ΔV_{apo}, to enter the elliptical transfer orbit and then a second impulsive burn, ΔV_{peri}, in order to circularize into the phasing orbit. The burns are performed in reverse once t_v has elapsed and $\Delta v = 0$.

$$r_{transfer\_apo} = a_0, \quad r_{transfer\_peri} = a_1, \quad r_{transfer\_peri} > r_{Earth} + 200km \tag{3-6}$$

$$\Delta V_{apo} = V_0 - V_{peri} = \sqrt{\frac{\mu}{r_{transfer\_peri}}}\left(1 - \sqrt{\frac{2r_{transfer\_apo}}{r_{transfer\_apo} + r_{transfer\_peri}}}\right) \tag{3-7}$$

$$\Delta V_{peri} = V_0 - V_{peri} = \sqrt{\frac{\mu}{r_{transfer\_apo}}}\left(\sqrt{\frac{2r_{transfer\_peri}}{r_{transfer\_apo}+r_{transfer\_peri}}} - 1\right) \quad 3\text{-}8$$

$$\Delta V_v = \Delta V_{apo} + \Delta V_{peri} \quad 3\text{-}9$$

We can also find the time it takes to phase the orbits, t_v, so that the satellites can align their v. It is calculated by using the Phasing Ratio which is the relation of the Δv to the original client orbit, number of orbits the servicer must stay in the phasing orbit (N_p), and the difference in the periods of each orbit, $T_0 - T_1$.

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \quad 3\text{-}10$$

$$\Delta v = |v_0 - v_1| \quad 3\text{-}11$$

$$Phasing\ Ratio = \frac{2\pi - \Delta v}{2\pi} \quad 3\text{-}12$$

$$N_p = \frac{Phasing\ Ratio\ T_0}{T_0 - T_1} \quad 3\text{-}13$$

$$t_v = N_p\, T_1 \quad 3\text{-}14$$

This phasing maneuver can also be done at a higher altitude above the client satellite but is not used for two reasons. First the servicer would have to cross the client satellite orbit which creates a collision risk, secondly the servicer must go to a lower altitude in order to execute a RAAN maneuver which is covered in the following section.

3.4 Leveraging environmental effects for orbital maneuver

We saw that in 3.1.1 that a direct plane change can be executed at the poles to execute a Ω change, however, this is extremely inefficient particularly in LEO. However, there are environmental effects that we can leverage in LEO that are not available to us in GEO.

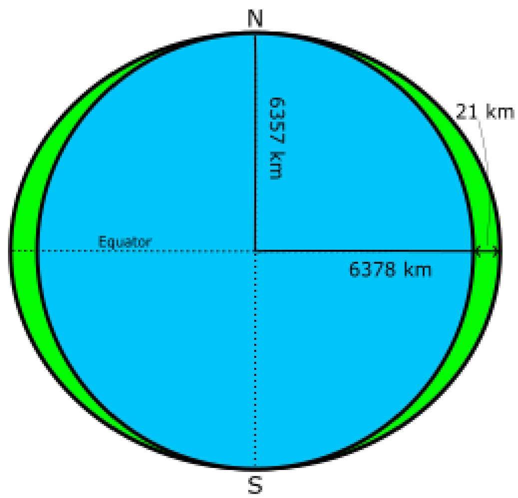

Figure 3-4 Earth is an oblate sphere and not a uniform sphere. This oblateness results in the J¬2 perturbation in orbital mechanics [116]

Due to the rotation of the Earth centrifugal forces are experienced which causes the Earth to bulge around the equator as seen in Figure 3-4, where the blue sphere represents what the size of the Earth would be if it were a uniform shape and the green circle represents the true nature of the earth where it bulges at the equator. Earth is not a perfect sphere and instead is an oblate spheroid. This difference in mass results in non-uniform gravitational forces on a satellite as it passes over the equator of the Earth. This results in more gravitational forces at the equator where satellites slow slightly and cause a westward drift of the satellite when in a prograde orbit [110]. This is also known as the J_2 zonal effect, $J_2 = 1.08262668 \times 10^{-3}$. The effect of this nodal drift, $\dot{\Omega}$, can be measured using the inclination, i, orbital period, T, and the semi-major axis of the orbit, a. The rate of nodal precession is largely a factor of altitude and inclination.

$$\omega = \frac{2\pi}{T} \tag{3-15}$$

$$\dot{\Omega} = \frac{3R_E^2 J_2}{2(a(1-e^2))^2}\omega \cos i \tag{3-16}$$

3.4.1 RAAN Change (Ω)

In 2014 Dr. Robert Legge proposed leveraging the J2 orbital perturbation to aid orbital maneuvers in order to achieve repeating ground tracks [29]. We can also leverage this effect to aid our ability to execute an $\Delta\Omega$ in order to move between the numerous planes of the pLEO constellation. This can be done by utilizing a Hohmann transfer to a lower orbit to create a difference in $\dot{\Omega}$ between the client orbit and a phasing orbit. By setting a phasing altitude, a_1, we can calculate the amount of time, t_Ω, it will take for a servicer to close the RAAN separation, $\Delta\Omega$, between planes.

$$\Delta\Omega = \frac{\pi}{planes} \tag{3-17}$$

$$\Delta\dot{\Omega} = \dot{\Omega}_1 - \dot{\Omega}_0 \tag{3-18}$$

$$t_\Omega = \frac{\Delta\Omega}{\Delta\dot{\Omega}} = \frac{\pi\left(\dot{\Omega}_1 - \dot{\Omega}_0\right)}{planes} \tag{3-19}$$

3.5 Propulsion

We will consider the use of both electric propulsion and chemical propulsion systems. Chemical propulsion (CP) systems benefit from a higher thrust level and can achieve desired speeds much more quickly than chemical propulsion but come at the expense of a high Isp, thus they remain less efficient in terms of mass. Electric propulsion (EP) systems have a much higher efficiency due to their high Isp but require continuous thrust maneuvers and achieve desired velocities over a much longer time than CP. EP systems are constrained by their ability to harness power as any additional mass for the solar arrays adversely effects the amount of inert mass that the satellite must carry.

3.5.1 Chemical Propulsion

We can calculate the masses required for the servicer to accomplish iterative orbital maneuvers for each success ΔV maneuver to enter and exit the phasing orbits. The mass is calculated using the Tsiolkovsky rocket equation below. CP monopropellant systems generally operate between 200-235 of Isp [117]. We will utilize an Isp of 230 seconds for our analysis. As the ΔV increases, the amount of propellant increases exponentially. This results in one of the most sensitive inputs to the system as an OOS servicer must be efficient in orbital maneuvers as it visits clients.

$$mass_{wet} = mass_{dry} e^{\frac{\Delta V}{g\ Isp}} \quad 3\text{-}20$$

$$mass_{propellant} = mass_{wet} - mass_{dry} = mass_{wet} \left(e^{\frac{\Delta V}{g\ Isp}} - 1 \right) \quad 3\text{-}21$$

3.5.2 Electric Propulsion

Many spacecraft are shifting towards EP systems due to their high efficiency due to their Isp being 500-3,000 seconds, which is substantially larger than CP systems by an order of magnitude [117]. EP systems have a tradeoff in the amount of thrust, F, they produce and the mass required to generate the power to provide that thrust P_s. Furthermore, the power delivered to the propulsion system is limited by the efficiency, η, as well as the characteristic of the power system, β. β has a range of 0.06-0.1 kg/W, for which we will use 0.06 for our analysis [117].

$$\eta = \frac{P_j}{P_s} \quad \text{3-22}$$

$$F = 2\frac{\eta P_s}{g\ Isp} \quad \text{3-23}$$

$$mass_{sa} = \beta P_s \quad \text{3-24}$$

The mass of the additional solar arrays, $mass_{sa}$, are additional inert mass which the OOS servicer will have to carry throughout the mission profile and will be adversely affect performance due to the rocket equation 3-20. We can execute a trade study to determine the effectiveness of an EP system over a CP system for a set of orbital maneuvers. Since the mass of the solar array is dependent on the power required by the thrust we will look at the effects of various thrust levels (0.02-0.08 mN) across a variety of ΔV ranges (5-400 m/s). We will hold $mass_{dry}$=1,000 kg, η=0.65, g=9.8 m/s, and Isp=3100 seconds which are standard performance characteristics for an EP system [117].

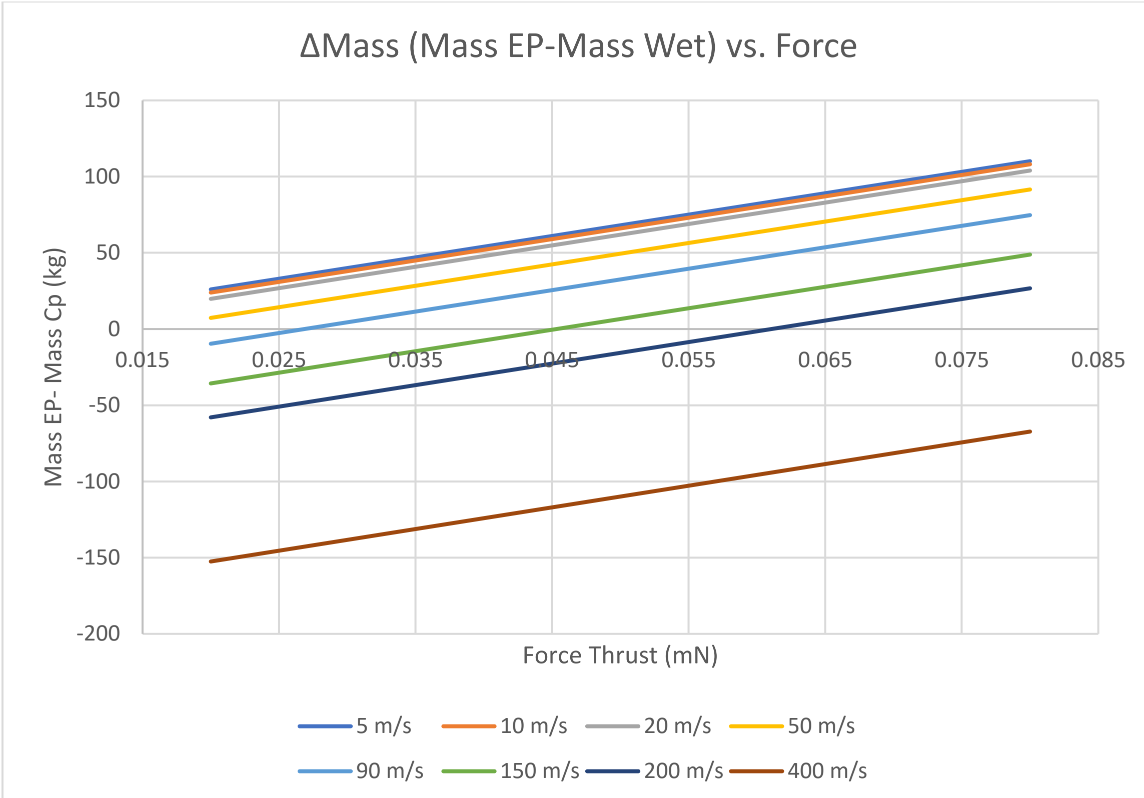

Figure 3-5 Tradespace on Mass of CP vs Mass of EP system

In Figure 3-5 we calculate the difference in mass, ΔM = Mass EP- Mass CP, using Eq. 3-20 through 4-14. We can see that lower thrust levels enable a smaller amount of inert mass to be carried which are advantageous lower solar array mass requirements, however these low thrust levels would result in significantly longer transfer times. The EP system does not achieve any mass savings until > 50 m/s. For longer duration missions and ΔV intensive maneuvers we shall use the highest thrust level possible. The most significant constraint on the EP system thrust level is the size of the solar array. We will bound the size of the solar array based on the known size of MEV-1 which has 23 m^2 of solar arrays that provide 10 kW of power [115].

Chapter

4. OOS Concepts of Operation

Our objective is to look at the general feasibility of an OOS system architecture for a pLEO constellation. There are an unlimited number of routes, methods, and maneuvers that can be used to rendezvous with each target in a pLEO constellation, we are looking to compare the feasibility of the OOS system across the variety of proposed pLEO constellations. This will be a first order analysis and a greater optimized solution exists for a particular constellation. Three Concepts of Operation (CONOPs) are of particular relevance to OOS.

Three CONOPs

1. Traditional – A spacecraft is launched to orbit with all of its resources onboard and carried throughout the mission as it visits each client.
2. Depots – Fuel or servicing depots are stationed throughout a constellation to aid in sustainment and reduce OOS mass requirements. The servicer moves between clients and the depot throughout the mission.
3. Pods – The servicer carries only consumable resources it needs for itself to maneuver throughout the constellation and the robotics package to execute

OOS on the client. Separate "Pods" are built as standalone satellites only to deliver servicing resources, such as fuel and parts, adjacent to the client satellites. The Pod is then captured by the OOS vehicle which then RPO with the client and executes transferring and installing the servicing resources. This system was originally proposed by Northrop Grumman for GEO applications [118].

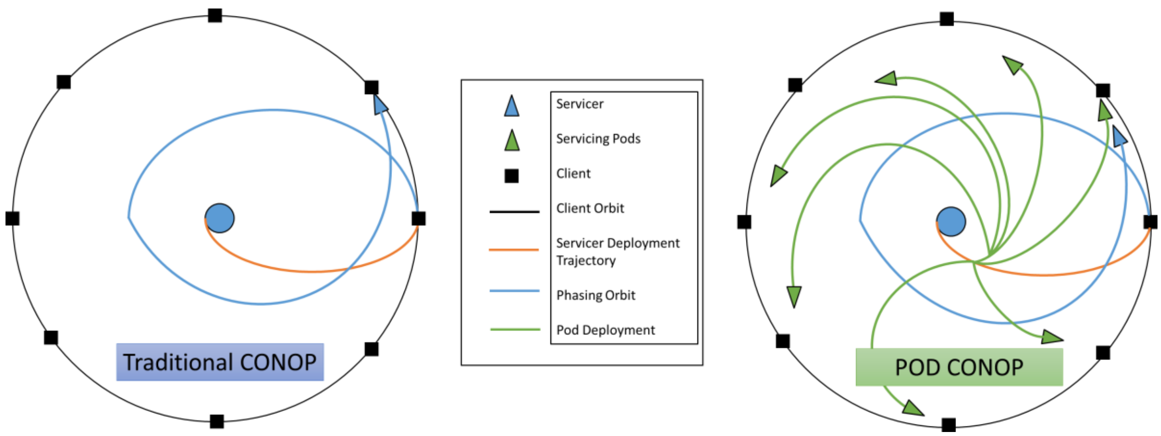

Figure 4-1 OOS CONOPs Traditional vs Pod

Previous analysis has been shown that the traditional method is inferior to the other options, the depot method is also sensitive to the constellation design and depot locations which result in an NP hard, traveling salesman problem. Additional research on OOS depot methods have been considered and are outside the scope of this paper [6,119,120]. Pods present the most beneficial CONOP to the general solution of an OOS system architecture.

The Pods lack the instantaneous propulsion, ACDS, RPO, sensing, and robotic equipment necessary to execute RPO with the client satellite. This reduces their manufacturing costs substantially and reduce the inert mass that the OOS must carry throughout the mission. This increases the utility of the OOS as those RPO systems are utilized more efficiently by only one or a few OOS servicers throughout the constellation.

4.1 Order of Maneuver

In order for the OOS servicer to move from one client to the next, it first must execute a RAAN change using the $\Delta\dot{\Omega}$ previously described in 3.4.1 which is depicted in Figure 4-2.

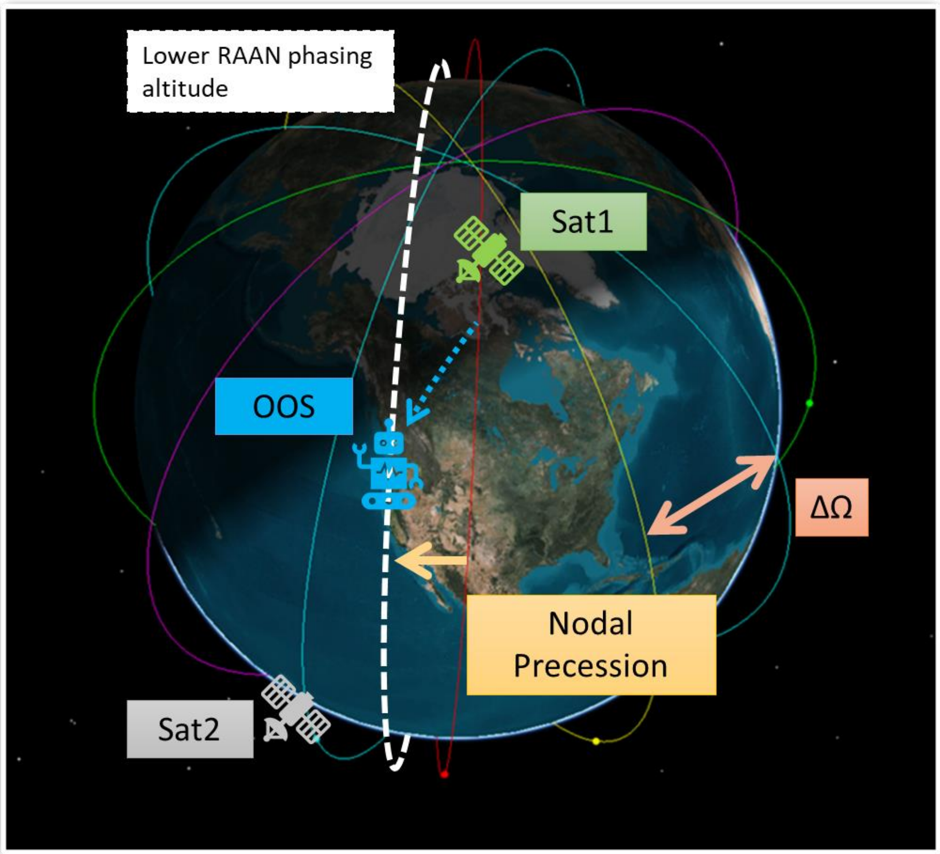

Figure 4-2 RAAN Change maneuver

Next the servicer OOS will execute the phasing maneuver to align the Δv as discussed in 3.3.2 and depicted in Figure 1-1.

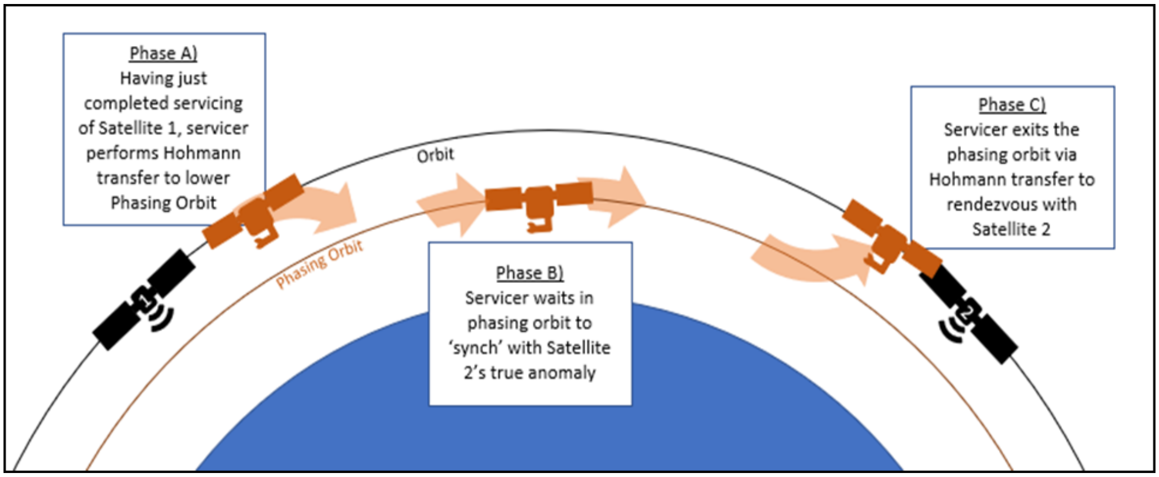

Figure 4-3 Orbital phasing to align v of the OOS and client sat

4.2 Assumptions

The OOS system assumes the following constellation parameters. Isp 240 (CP) monopropellant and 3100 (EP) seconds hall-effect thruster from section 3.5, inclination of 53 degrees based on the pLEO constellations covered in 2.1.1. The input parameters for the OOS system architecture that will be determine the tradespace are listed in Table 4-1. We must select a lower altitude to execute the RAAN phasing maneuver. Since we have a variety of client altitudes from 500-1,500 km, we will choose a variety of RAAN phasing altitudes as a ratio of the original client altitude, ρ.

Variable	Description	Range	Units
N	Number of client satellites	[1 - 100]	-
m	Mass of servicing resources delivered	[1 - 860]	kg
a_0	Altitude of client satellite	[500, 750, 1000, 1500]	km
ρ	RAAN Phasing Ratio	[0 - 1]	-
PS	Propulsion system	[0=CP, 1=EP]	-

Table 4-1 Input design variables for OOS system tradespace

There are several constraints. The OOS wet mass < 63,800 kg since this is the maximum payload capacity for a SpaceX Falcon 9 Heavy to LEO [121]. The phasing altitude > 200 km as any lower would cause significant atmospheric drag and possibly crash into Earth. The overall servicing time < 7 years as this was the design life for the constellations discussed in 2.1.1. The maximum servicing mass delivered is based on the mass of the Iridium next satellite [122].

4.3 Costs

We derive the cost of the of the OOS wet mass from the previous OOS missions. We will utilize a satellite cost model which is scaled according to the OSAM-1 mission since our servicer will share the legacy as a LEO servicer. The early Technology Demonstration Level (TRL) demonstration missions have higher costs than their follow-on commercial and operational systems. For comparison we will look at the original GPS system costs of FY95 $14.1B (FY21 $24.5B) vs the latest GPS Block III costs of FY18 $7.2B (FY21 $7.6B), which provides a 69% decrease in costs for follow-on programs. The total OSAM-1 mission costs are estimated at $1.1B through 2024 with a wet mass of 6,500 kg, accounting for our 69% decrease in technology transfer and legacy heritage this results in a OOS wet mass cost of 5.07×10^2 $M/kg [113,123].

$$Cost_{OOS} = 5.07 \times 10^2 \; mass_{oos} \tag{4-1}$$

The OOS PODs are calculated in a similar fashion based on the cost of the Iridium Next constellation and the Small Satellite Cost Model (SSCM). Since there are a large number of Pods we apply a learning rate, S (0.85), for serial production over 50 units, N, in Equation 4-14. [124].

$$L = N^{\left[1-\frac{\ln(\frac{1}{0.85})}{\ln 2}\right]} \qquad 4\text{-}2$$

Iridium Next cost $2.9B to deploy 81 satellites at 860 kg each, by using this cost as the mass baseline for the delivery of servicing resources we result in a modified SSCM by incorporating L in Equation 4-3 [122,124].

$$Cost_{pod} = L(0.021\, mass_{pod}{}^{1.1}) \qquad 4\text{-}3$$

Launch costs are assumed on a Falcon 9 Heavy LEO launch ride share. This is calculated using the $90M total launch cost at a max total payload of 63,800 kg, resulting in a launch cost of 1.41 x 10^3 $M/kg [121].

$$Cost_{launch} = 1.41 \times\ 10^3\ (mass_{oos} + N\ mass_{pod}) \qquad 4\text{-}4$$

The total overall mission costs are provided by combining all costs, $Cost_{launch}$.

$$Cost_{launch} = Cost_{oos} + N\ Cost_{pod} + Cost_{launch} \qquad 4\text{-}5$$

4.4 Performance/Utility

The performance of the OOS system is measured by its overall utility. Due to the complexity of the OOS multiple different attributes can be prioritized. In order to reduce the performance metric to a singular variable we must normalize the desirable attributes of the system. In order to normalize the performance metric, we will use Multi-Attribute Utility (MAU) which enables a complex system to be evaluated by several different attributes into a singular utility value, U(X) [125]. There are several attributes which are desirable for an OOS system – timeliness, number of servicing events, and mass delivered. These single attribute utilities, $U(X_i)$, are aggregated in the MAUT Keeney-Raiffa function in Equation 4-14 [125]. The weighted sum of k_i in Equation 4-14 normalize the overall total utility to 1.

$$KU(X) + 1 = \prod_{i=1}^{N} (Kk_i U(X_i) + 1) \tag{4-6}$$

$$\sum k_i = 1 \tag{4-7}$$

4.4.1 Timeliness

The ability to quickly and efficiently service is critical to an OOS system. As each constellation has a limited design life, the servicing is not useful if a satellite experiences partial or full failure before the OOS arrives. The timeliness utility is governed by the half-life, $t_{1/2}$, which is determined by the design life, t_d, and the failure rate of satellites, $1 - N(t_d)/N_0$.

$$t_{1/2} = -\frac{t_d}{\log_2\left(1 - \frac{N(t_d)}{N_0}\right)} \tag{4-8}$$

$$\tau = -\frac{t_{1/2}}{\ln 2} \tag{4-9}$$

$$U_{time} = e^{\frac{t_{service}}{\tau}} \tag{4-10}$$

We can set a baseline decay rate by the 30% failure rate of the original Iridium constellation [48]. Then we can vary the amount of failure rates to compare the utility of servicing those constellations more quickly in Figure 4-4 and we can also plot the % of all satellite failures across the same time frame in Figure 4-5.

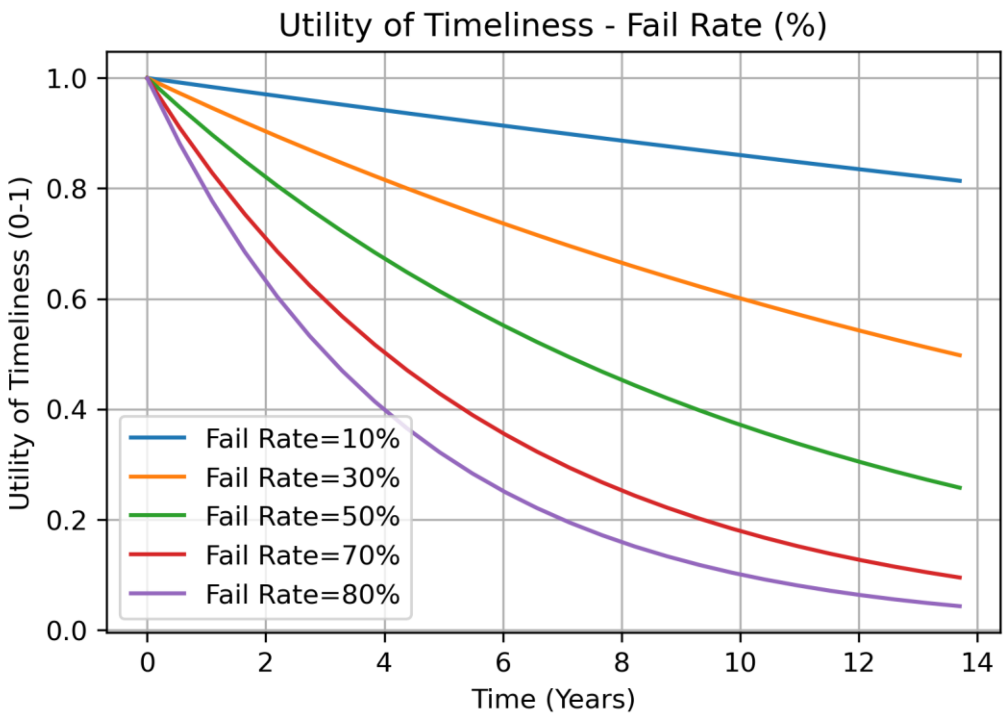

Figure 4-4 Utility of time based on failure rate

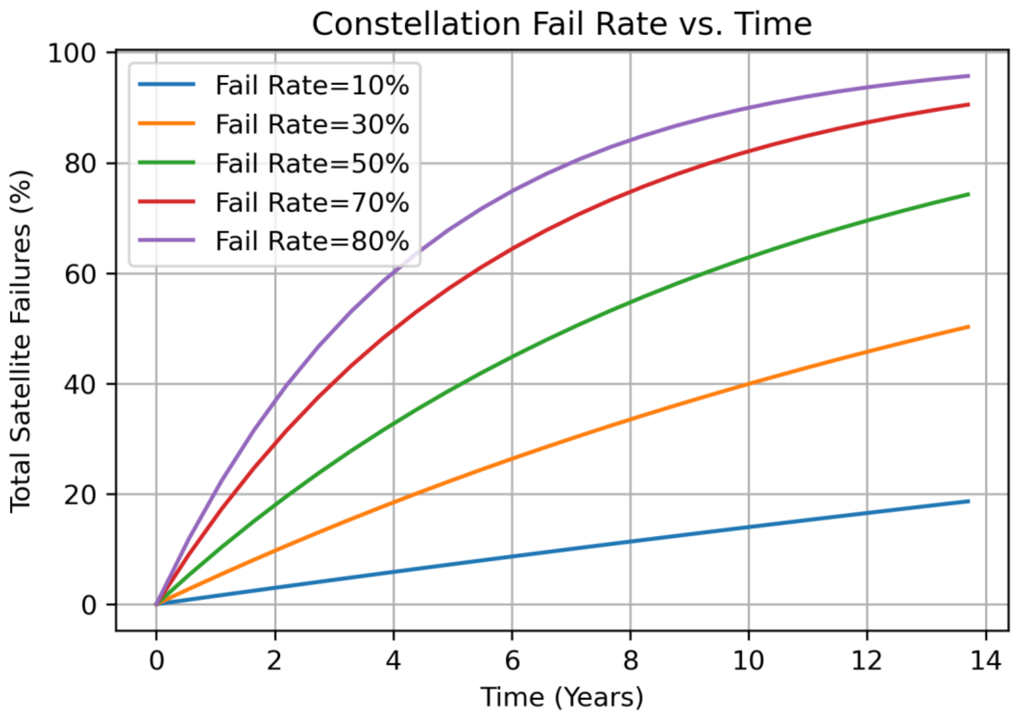

Figure 4-5 Satellite failure rates over time.

In Figure 4-4 as the failure rate increases there is a loss of utility due to the OOS not arriving in time to mitigate or prevent constellation outages, this corresponds to more emergent circumstances in which an OOS is expected to travel quickly to the service the client. This increase in failure rate also corresponds to lowering the reliability and mission assurance requirements of the satellite which we will later compare in the trade study. The lower failure rates represent a more reliable system that has increased reliability and mission assurance requirements, you can also see in Figure 4-4 that these lower failure rates result in less penalty on the timeliness of service.

4.4.2 Number of servicing events

If an OOS were only able to service one client there would be little value in servicing, since a replacement satellite could have been launched it its place. The utility of the number of servicing events, U_{events} , is provided by the number of clients serviced, N , and the max number of satellites, $N_{max} = 100$. The utility of servicing events is plotted in Figure 4-6. When only a few clients are serviced there is little utility in servicing only a small portion of the constellation. As the OOS system visits more clients it achieves greater utility.

$$U_{events} = \frac{\ln N}{\ln N_{max}} \tag{4-11}$$

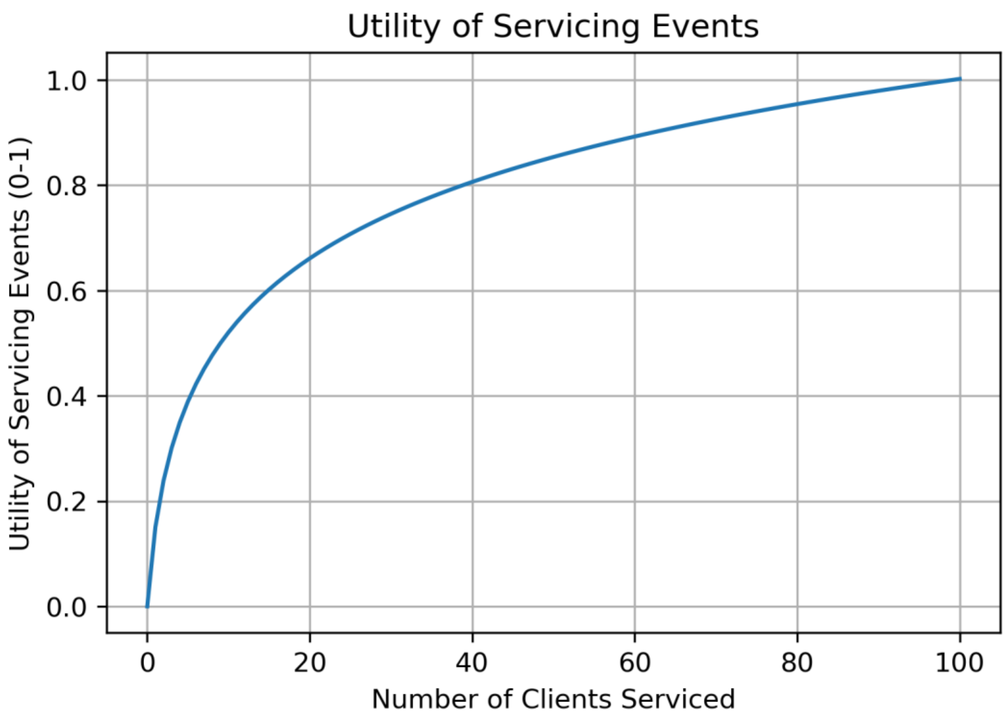

Figure 4-6 Utility of servicing events

4.4.3 Mass Delivered

A critical consideration for an OOS is what capabilities it can deliver or enable to a client. These capabilities can take the form of replacement parts to fix malfunctioning components, propellant to enable maneuvering and station keeping, or improved payloads to upgrade the client satellite capabilities. The tradespace normalizes this attribute by using the inert mass delivered to the client satellite. The utility for servicing mass delivered, U_{mass} , is provided below in Equation 4-14, the utility is normalized to the client mass, $mass_{client}$. As the delivered servicing mass, $mass_{del}$, approaches the client mass, this represents significant enhancement to services. When the delivered mass matches the client mass this represents a total replacement which provides the maximum utility of 1. The mass utility is plotted in Figure 4-7.

$$U_{mass} = \frac{\ln(N\, mass_{del})}{\ln(N\, mass_{client})} \quad \text{4-12}$$

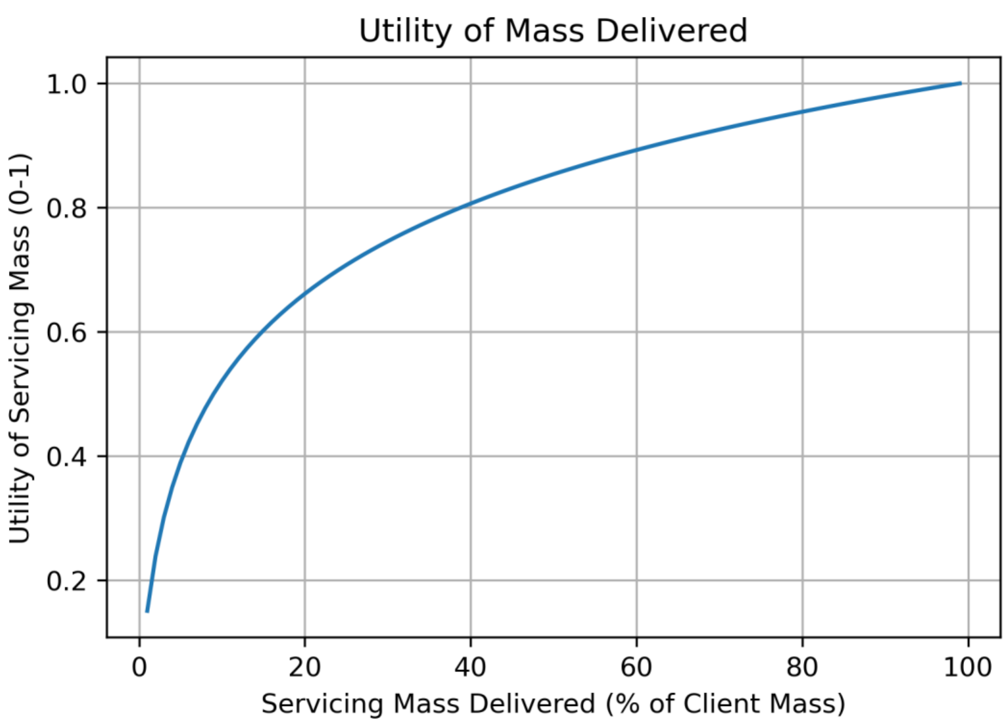

Figure 4-7 Utility of servicing mass delivered as a % of client mass

Finally, the total utility from Equation 4-6 and 4-7 is aggregated together in Equation 4-13. The k_i weighting can be chosen by either the OOS operator or the client. A higher k_i value allocates an increased weighting or priority for that particular attribute over the others.

$$KU(X) = k_1 U_{time} + k_2 U_{events} + k_3 U_{mass} \quad \text{4-13}$$

$$k_1 + k_2 + k_3 = 1 \quad \text{4-14}$$

4.5 Comparative Alternatives

To determine the utility and value of an OOS system we must compare it to a comparative alternative. The comparative alternatives are to use spare satellites – ground and orbital spares. Ground spares offer flexibility in their ability to respond to unforeseen failures within the constellation, however their ability to respond is also reliant upon the scheduling and preparation for launch which can take several months. Ground spares face the same manufacturing and launch costs as orbital spares. Since ground spares face this delay in deployment to orbit at the same costs we will leverage the orbital spares system which Iridium leverages.

Iridium spare satellites remain equally distributed and parked in orbit at 666 km [43], this lower altitude allows the spare satellite to leverage the difference in orbital period for the phasing maneuver discussed in 3.3.2, In-Plane Maneuver (a, v). Within the inclined orbits a spare satellite at a lower altitude can make use of the RAAN change maneuver discussed in 3.4.1, Leveraging environmental effects for orbital maneuver. Combining these two maneuvers we can calculate the total time it would take for a spare satellite to reach the furthest client satellite.

The same cost model is used in 4.3 Costs minus the cost of the OOS system. The manufacturing cost for each spare and launch costs are only considered with the learning rate applied. The spares mass is matched to the client mass which is also matched to the maximum OOS mass delivered as described in 4.4 Performance/Utility -Mass serviced. For the tradespace we will include the utility vs. cost as the alternative to OOS which is also the current paradigm and methodology for addressing on-orbit failures.

Chapter

5. Tradespace

5.1 Current Paradigm

For the first several scenarios we will analyze the utility of an OOS system architecture within the current paradigm for high levels of system reliability and mission assurance. In the current paradigm we use the 30% failure rate from 4.4.1 which was relatively high due to Iridium's 30 satellites which failed in orbit by the time the second generation of Iridium was launched in 2019 [48]. We will explore several scenarios based on what different satellite operators and clients would prioritize for an OOS system architecture, this is done through selecting the weighting, k_i, values from the MAUT. For the first tradespace we will evenly distribute the k_i values, then we will explore the effects of biasing individual attributes. We adopt the previous assumptions from Table 4-1 and include additional parameters for the model below.

Variable	Description	Range	Units
C	Clients per plane	[1-20]	-
P	Number of client planes	[1-72]	-
N	Number of client satellites	[1 - 1440]	-
S	Number of spare satellites	[1 - 100]	-
$mass_{del}$	Mass of servicing resources delivered	[0 - 860]	kg
a_0	Altitude of client satellite	[500, 750, 1000, 1500]	km
Pr	RAAN Phasing Ratio (higher is slower phasing)	[0 - 1]	-
PS	Propulsion system	[0=CP, 1=EP]	-

Table 5-1 Design input for tradespace

Variable	Description	Value	Units
$mass_{OOSdry}$	Dry mass of OOS	1000	kg
$mass_{client}$	Mass of client satellite	860	kg
i	Inclination of orbit	53	deg
Δv	Difference in true anomaly for phasing	π	rads
Isp_{CP}	Isp for chemical propulsion	230	sec
Isp_{EP}	Isp for electric propulsion	3100	sec

Table 5-2 Parameters for tradespace

Variable	Description	Constraint	Units
a_{peri}	Lower altitude limit for altitude phasing	>200	km
$mass_{OOSwet}$	Wet mass of OOS launch limit	63,800	kg
t_{total}	Total servicing time limit	14	years

Table 5-3 Constraints for tradespace

5.1.1 Scenario 1 – Balanced

By selecting to equally distribute the weighting coefficients across the three k values, this results in 1/3 being equally divided amongst the three. This would be a case where a satellite client or customer is equally concerned about being timely, reaching as many clients as possible, and delivering as much mass as possible.

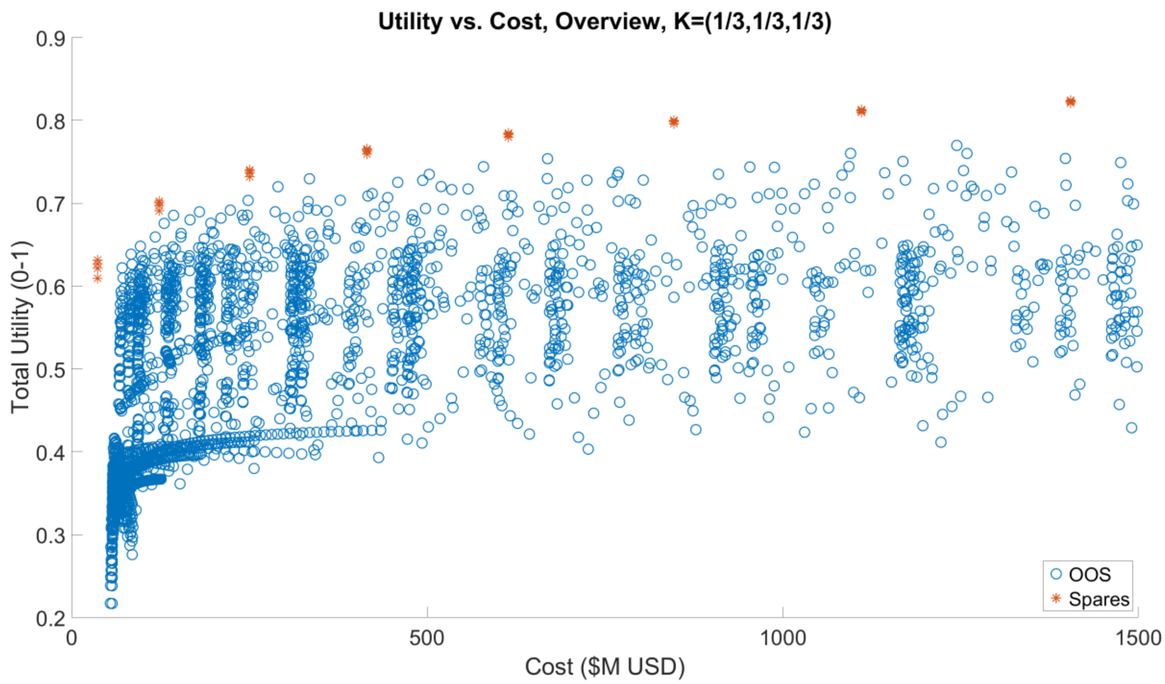

Figure 5-1 Scenario 1 - Tradespace utility vs cost overview

$$Scenario\ 1 = \left[k_1 = \frac{1}{3},\ k_2 = \frac{1}{3},\ k_3 = \frac{1}{3}\right]$$

In Scenario 1 where every utility is equal in weighting, we can see that no OOS solution provides greater overall utility than the alternative spares solution in Figure 5-1.

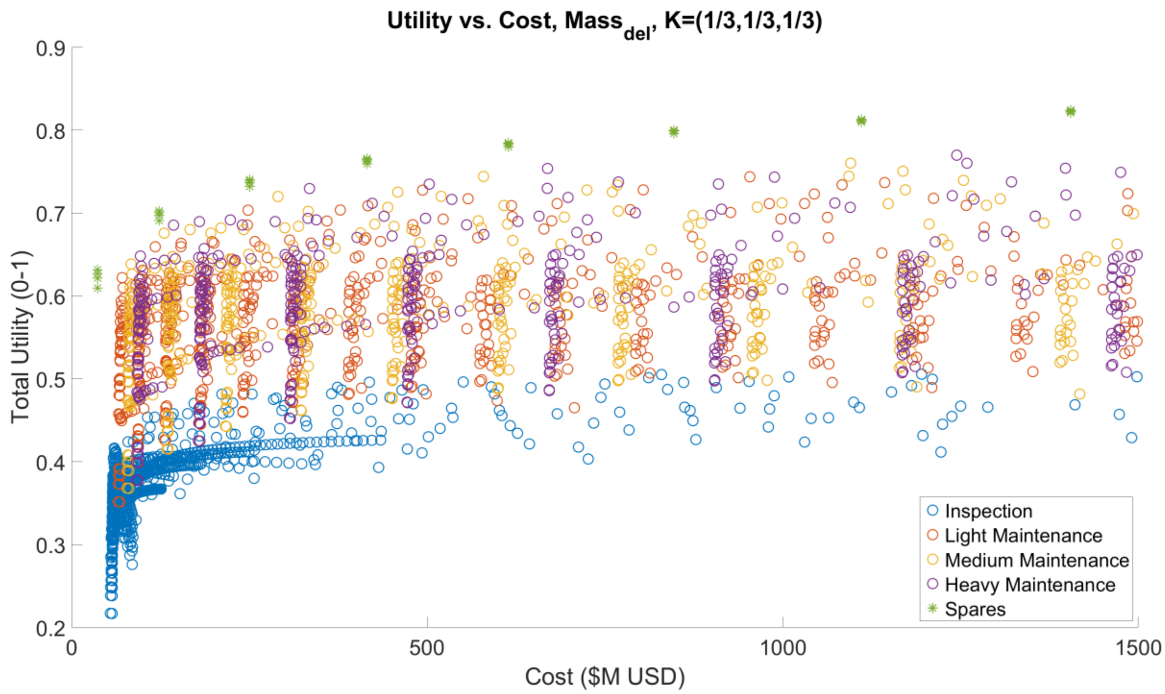

Figure 5-2 Scenario 1 - Tradespace trends and division by mass delivered

In Figure 5-2 we take the previous general overview and highlight the different amounts of mass that each OOS design delivered to each client, $mass_{del}$. We can see that all of the inspection OOS designs which did not deliver any fuel, $mass_{del}=0$ highlighted in blue, severely underperformed the rest of the solutions. Taking a closer look at the pareto front in Figure 5-3 the spares solution sits on the pareto and the OOS solutions make up the dominated space. However, the spacing and trends of the solution as the spare satellite population, S, increases from one to five we see diminishing utility and the vertical spread between the different altitudes decreasing as the highlighted orange circles. The size of the circle represents a greater difference in the overall utility, which decreases in size as S increases.

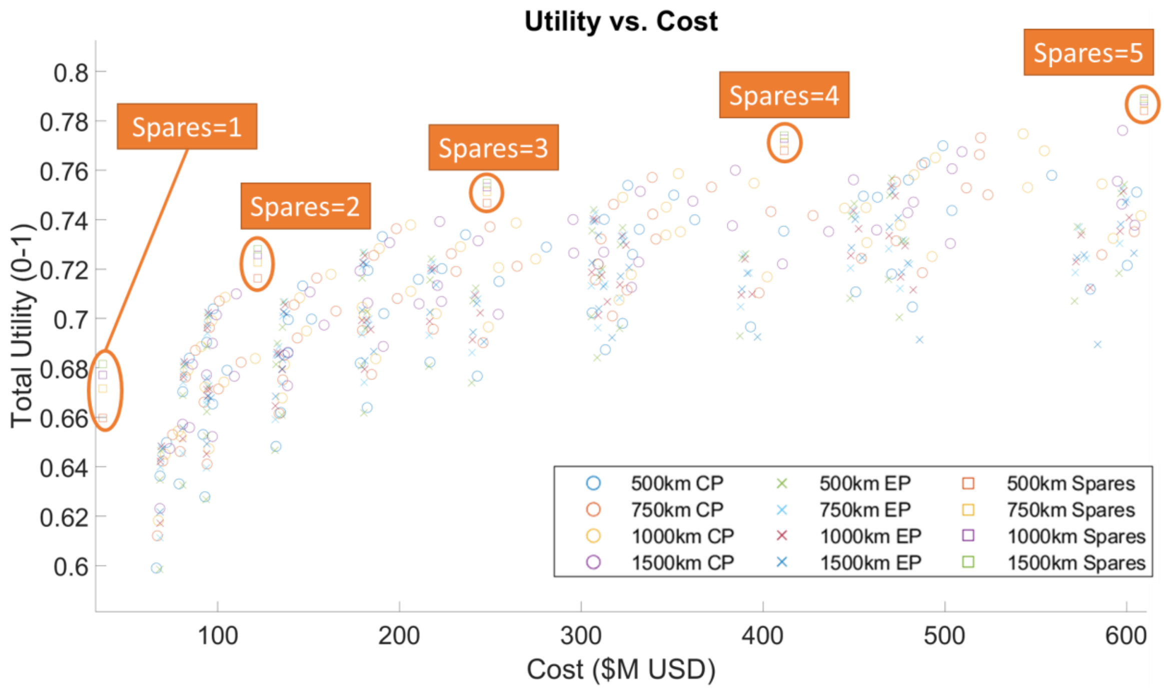

Figure 5-3 Scenario 1 - Spares diminishing returns

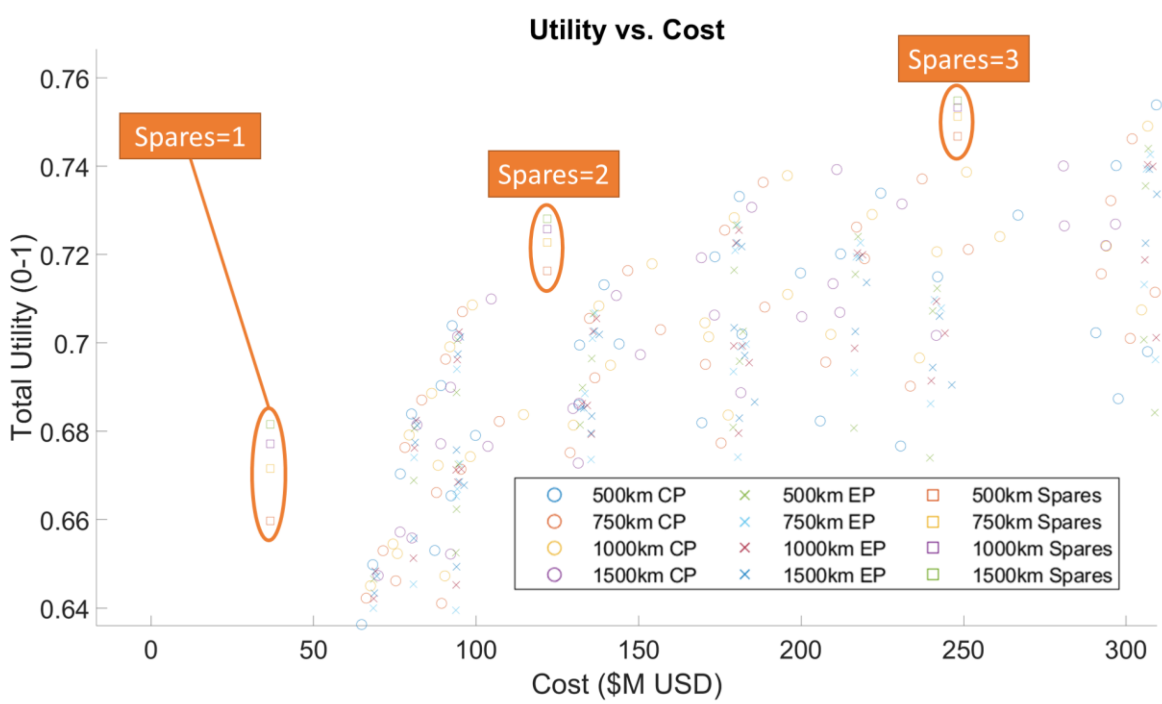

Figure 5-4 Scenario 1 - Spares cluster comparisons of utility gap

The decrease in the vertical spread of utility can be seen more clearly in Figure 5-4 when comparing S = (1, 3). The lines are vertical as there is no penalty based on the altitude where the spares are inserted. We begin to see the spares solution for all of the client altitudes clustering as S increases. This is due to the phasing altitude having a greater difference between the operational client orbit and the parking orbit. At higher altitude, spare satellites can create greater phasing differences which allow for faster transfers which increases the utility of timeliness. As the number of spares increase from one to three we can see the advantages of the higher altitude diminish since the spares are more equally spaced throughout the constellation which reduces the Δv and $\Delta\Omega$ for each spare to reach its furthest client satellite. We can also see that no OOS solution achieves nearly the same utility as S = 1. But as S increases, the OOS designs begin to close the gap in performance as economies of scale become advantageous to the OOS system.

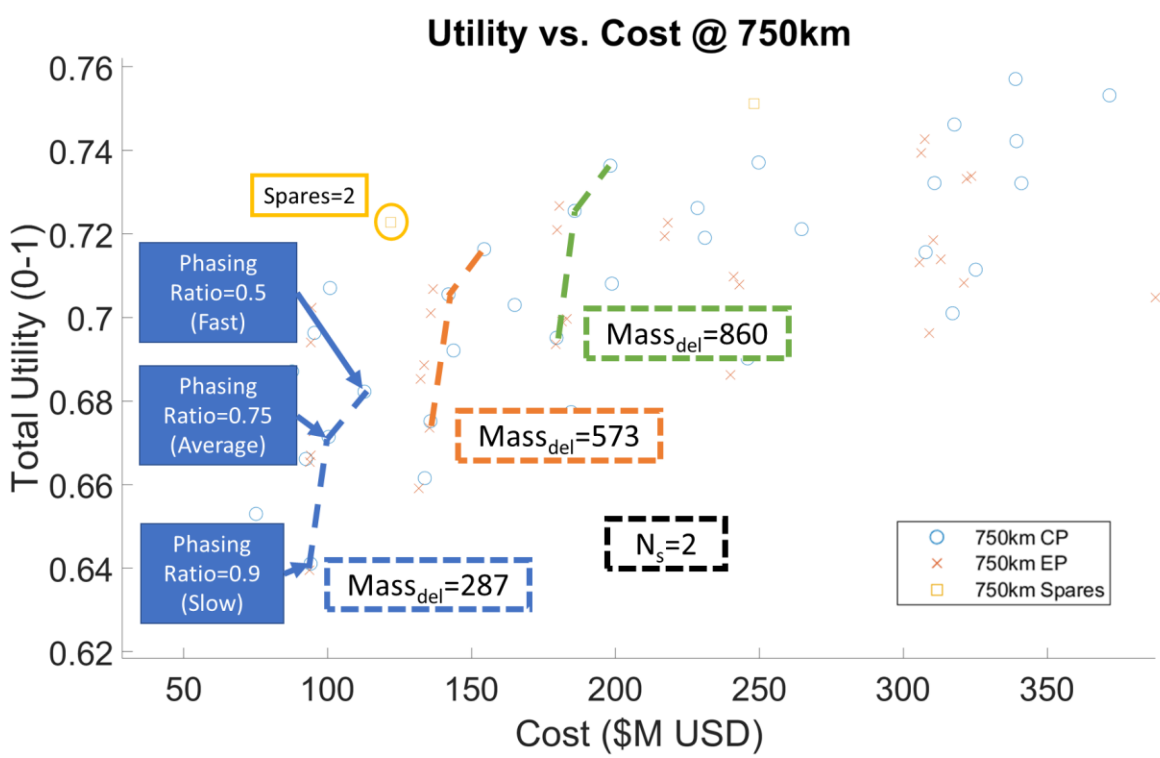

Figure 5-5 Scenario 1 – 750km pareto front design sensitivities

We can isolate an individual altitude to analyze the effects of various design changes. Each of the altitudes have very similar plots and trends. Isolating the results for a_0 = 750km, we compare the OOS results for Figure 5-5 for the number of servicing events, N_s = 2. The three vertical trendlines are separated by the amount of mass that was delivered. As each OOS system delivered more servicing mass it begins to approach the spares alternative, but does not achieve better performance for this scenario. The vertical colored trendlines are made up of three points each. The bottom most point has an altitude phasing ratio = 0.9, which is the most fuel economical but takes the most time to transfer due. The middle point has a phasing ratio = 0.75, which requires more propellant mass to transfer to a lower phasing orbit but provides better transfer times increasing the overall utility for not much more cost. The top most point has the lowest phasing ratio = 0.5, this more aggressive transfer increased the OOS wet mass, and thus cost, such that it provided less overall utility increase compared to the highest phasing ratio. The $mass_{del}$ are equally divided by three from the highest amount of mass that can be delivered which is the mass of the client, $mass_{client}$ = 860 kg based on the Iridum satellite. A continuous value is not used otherwise the dominated space becomes too cluttered for analysis but the trends hold.

5.1.2 Scenario 2 – Urgent Servicing

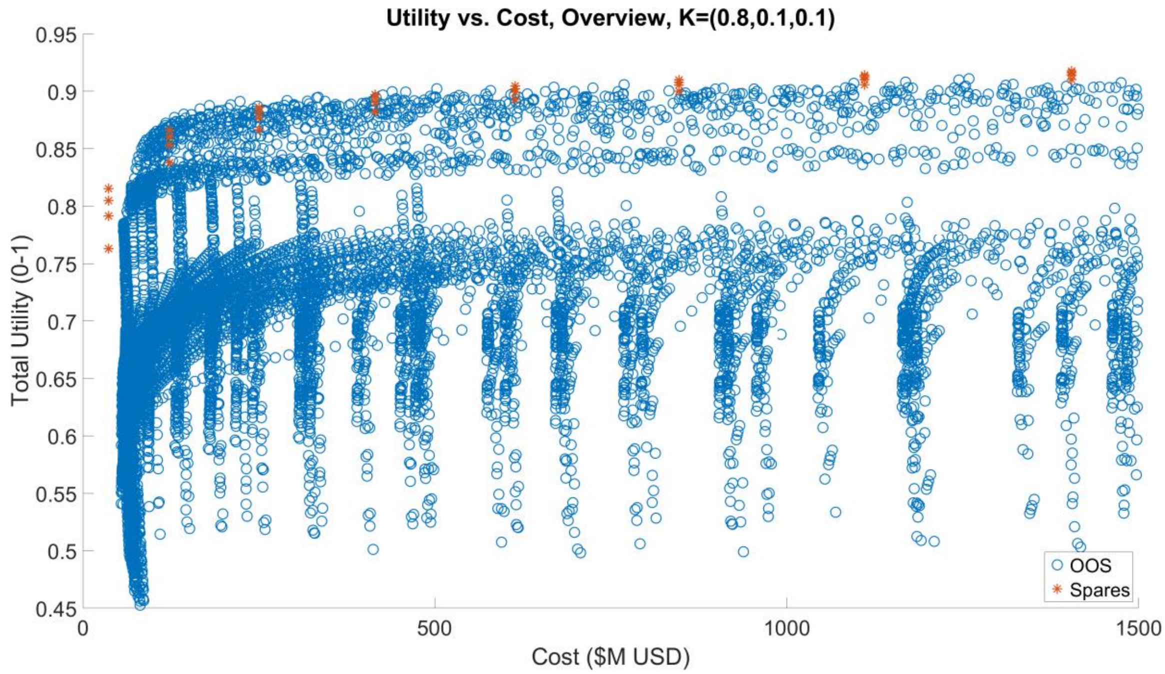

Figure 5-6 Scenario 2 – Tradespace overview

$$Scenario\ 2 = [k_1 = 0.8,\ k_2 = .1,\ k_3 = .1]$$

In Scenario 2 we place a majority of our MAUT weighting on the timeliness utility. The remaining 0.2 are equally distributed 0.1 to both the number of events and the delivery mass. This scenario would be relevant for any client that has a critical system which requires immediate attention or a satellite constellation that requires extremely high resiliency or reliability. This OOS system could also augment a crewed space system architecture where safety, flexibility, and response are critical. We can see from the overview in Figure 5-6 that OOS provides many superior solutions at the pareto front. The spares solution increases by one satellite from left to right.

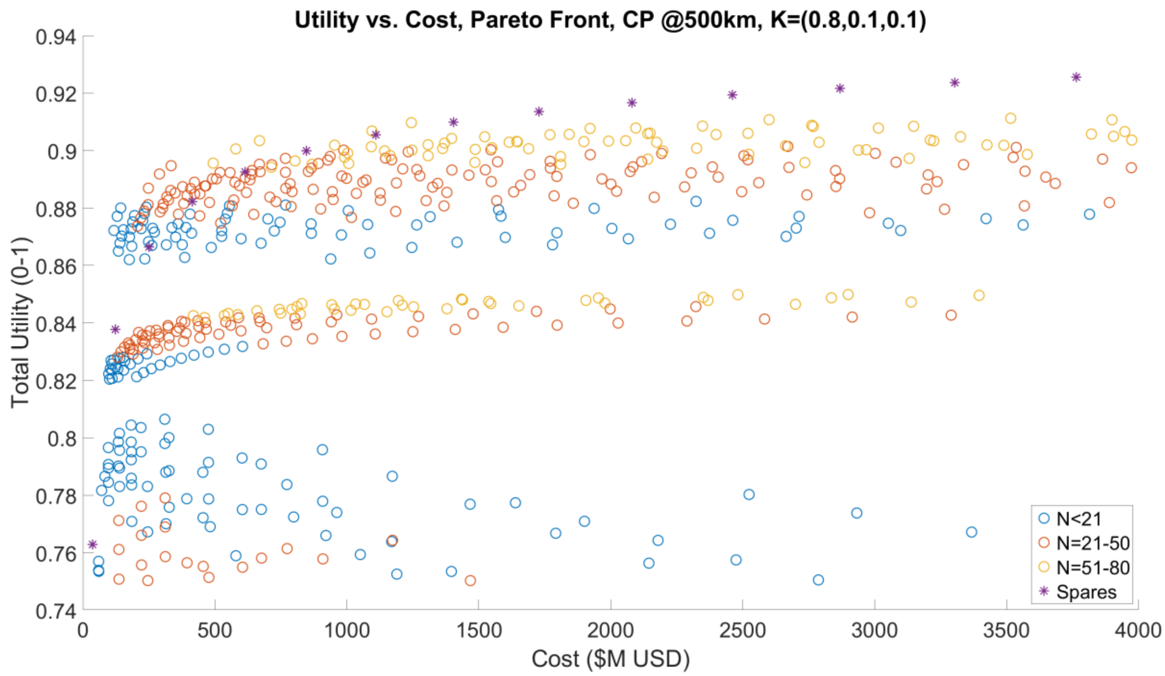

Figure 5-7 Scenario 2 - Pareto front at 500km

Isolating the pareto front of CP solutions at 500km in Figure 5-7, the OOS provides a higher performing solution for Scenario 2 while the spares are low in number. Eventually as costs grow and spares approach the replacement constellation the utility of OOS falls behind the alternative option of entire constellation replacement. The lower number of $N < 21$ clients served, in blue, provides greater utility over $S = 1$ to $S= 3$. Then $N = 21$ to 50 provides greater performance over $S = 4$ to $S = 5$. After which $N = 51 - 80$ performs better until $S = 7$ at which point the spares solution provides better overall performance.

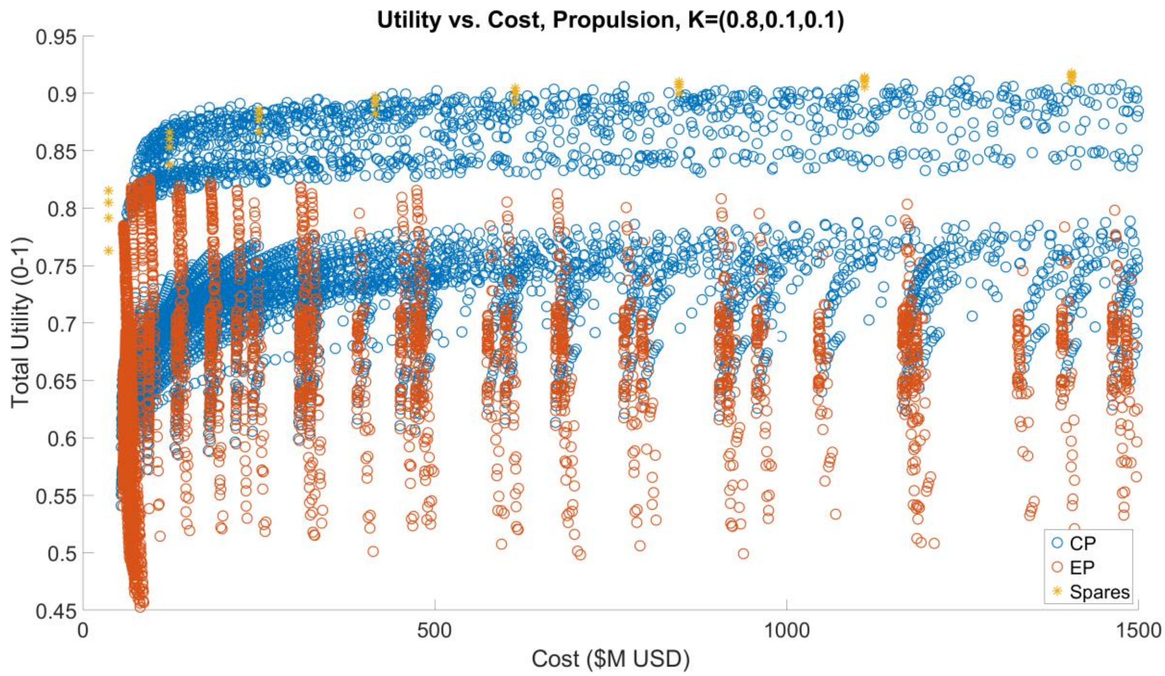

Figure 5-8 Scenario 2 – Tradespace comparing propulsion systems

In Figure 5-8 we can compare the propulsion systems between EP and CP, the EP systems occupy the dominated space and we can see that it provides inadequate response time when the timeliness of service is a priority. This is due to the extremely long time of flight (TOF) which EP systems require for executing their orbital maneuvers.

The type of servicing corresponds to the amount of $mass_{del}$ the OOS provides to the client. From the lowest $mass_{del}$ to the highest they correspond to inspection, light maintenance, medium maintenance, and heavy maintenance respectively. Figure 5-9 shows the effect of servicing mass delivered for this scenario. The significant trend of note is that the inspection service provides limited value in this case. Even in this Scenario 2 when timeliness is highly critical, OOS can provide higher utility solutions in some circumstances.

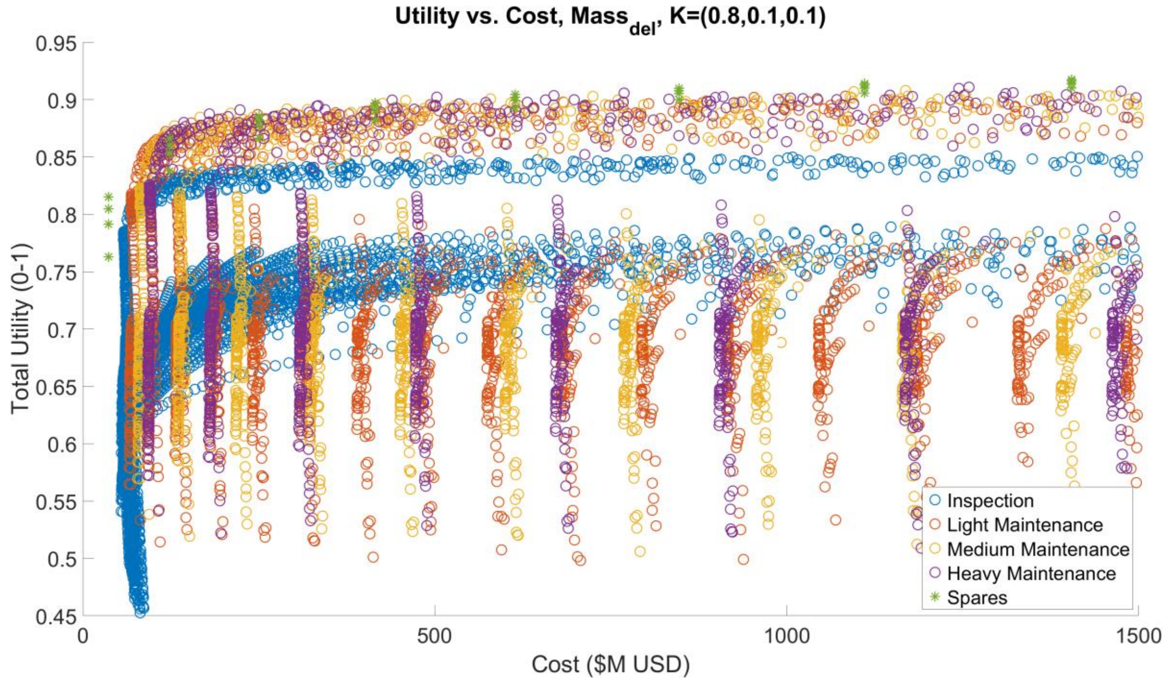

Figure 5-9 Scenario 2 – Tradespace comparing servicing mass delivered

5.1.3 Scenario 3 – Quantity

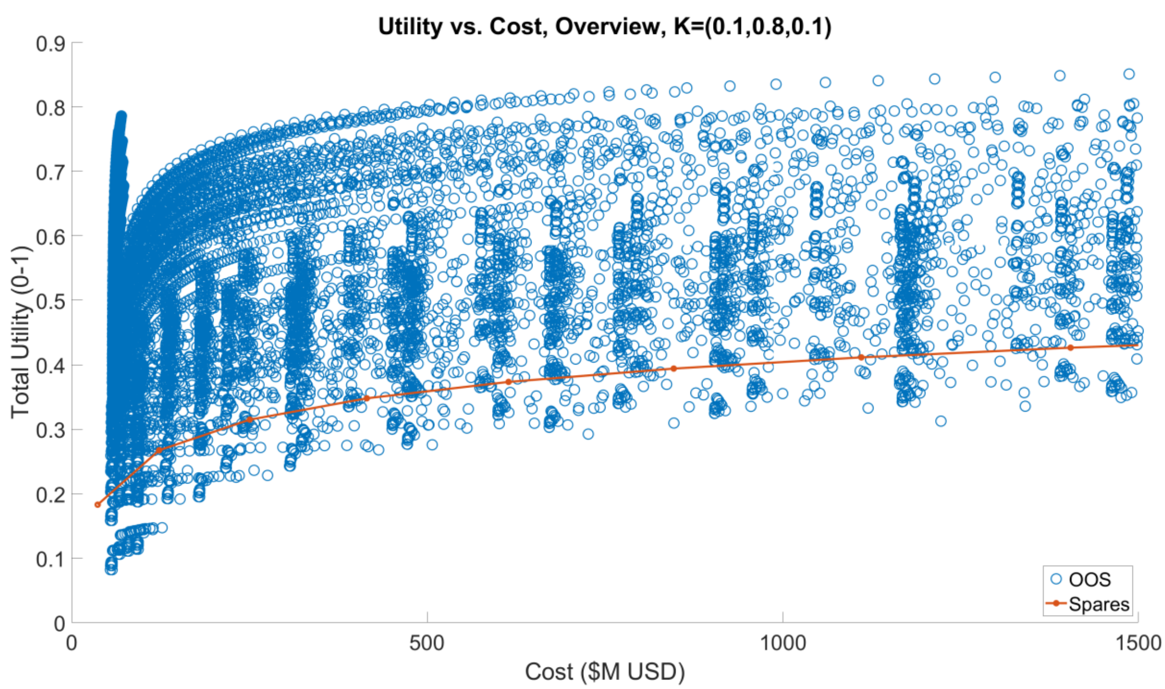

Figure 5-10 Scenario 3 – Tradespace overview

Figure 5-11 Scenario 3 – Tradespace by altitude

$$Scenario\ 3 = [k_1 = 0.1,\ k_2 = 0.8,\ k_3 = 0.1]$$

For Scenario 3 we will weigh the attribute associated with servicing the highest number of clients. This would be beneficial for satellite clients who are seeking to achieve the lowest cost for servicing as they can reach more of their constellation or an OOS operator who is trying to generate as many servicing opportunities as possible. In the general tradespace overview in Figure 5-10 we can see that the alternative spares solution performs quite poorly with their solution being inferior to the dominated space of a majority of the OOS solutions. This scenario makes OOS extremely advantageous over the spare solution, this is due to the OOS solutions being able to reach significantly more targets compared to the spares solution.

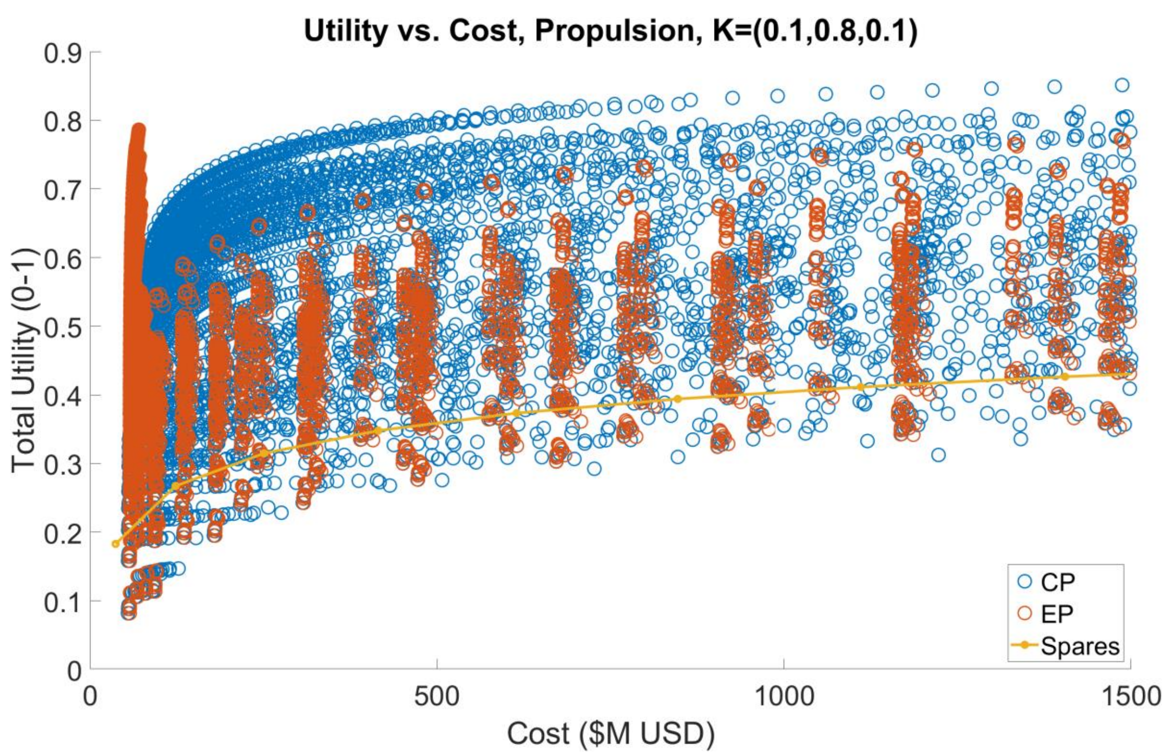

Figure 5-12 Scenario 3 – Comparing propulsion type

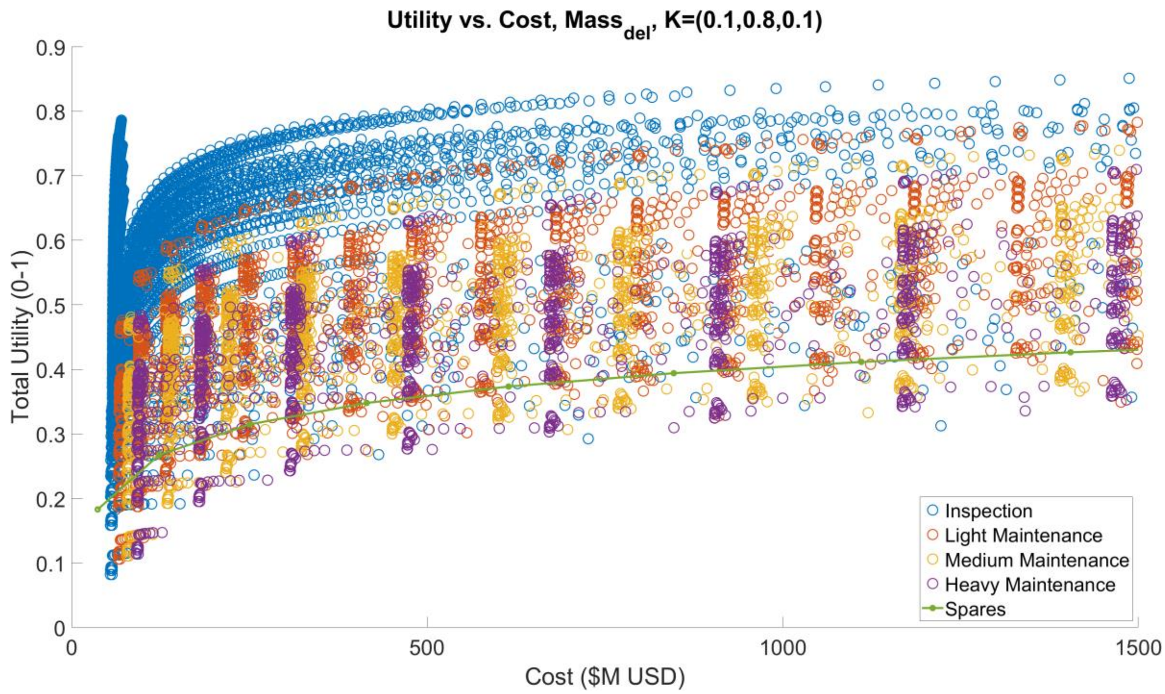

Figure 5-13 Scenario 3 – Comparing $mass_{del}$ for servicing type

In Figure 5-12 we compare the effects of propulsion type on the tradespace. We can see the EP solutions provide significantly higher performance on the far left of the tradespace for a nearly vertical trend in utility, the vertical results of EP are bounded by the total maximum time allowed for this analysis, 14 years. While in Figure 5-13 we can see that the amount of $mass_{del}$ also correlates with high utility along the pareto front. We combine these two characteristics at a single altitude of 1,500 km to compare the relationship between the two in Figure 5-14. Inspection EP OOS solutions provide the highest utility due to their efficiency and conservation of mass due to their efficient propulsion systems allowing them to reach more targets. This comes at the expense of servicing times as these solutions have the slowest servicing times seen in Figure 5-15. Where the slowest inspection EP solutions dominate the pareto front but take 9.3 years to service 700 clients.

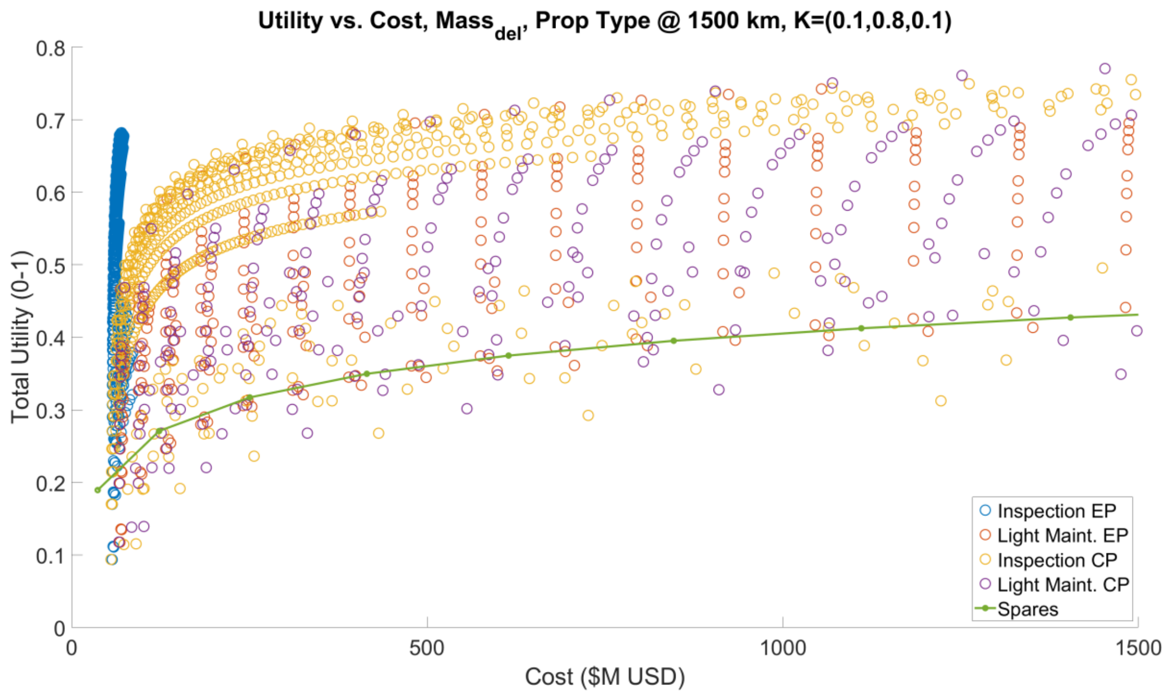

Figure 5-14 Scenario 3 – Comparing mass$_{del}$ and prop type at 1,500 km

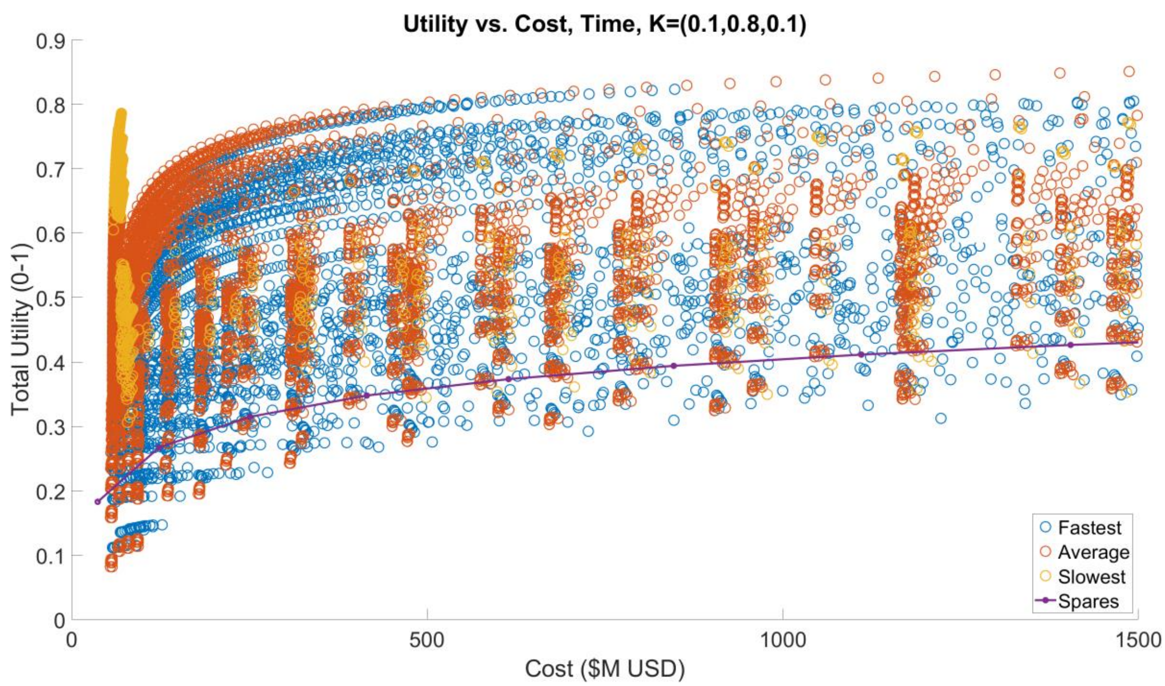

Figure 5-15 Scenario 3 – Comparing overall servicing time

Scenario 3's weighting scheme would likely be beneficial for a an OOS system that intended on doing high volume EP inspections. Relatively high performance was also seen from the light maintenance case for the CP solutions in Figure 5-14. In this case OOS provides an attractive and ideal option compared to the spares solution which makes it well suited to complementing pLEO constellations.

5.1.4 Scenario 4 – Mass

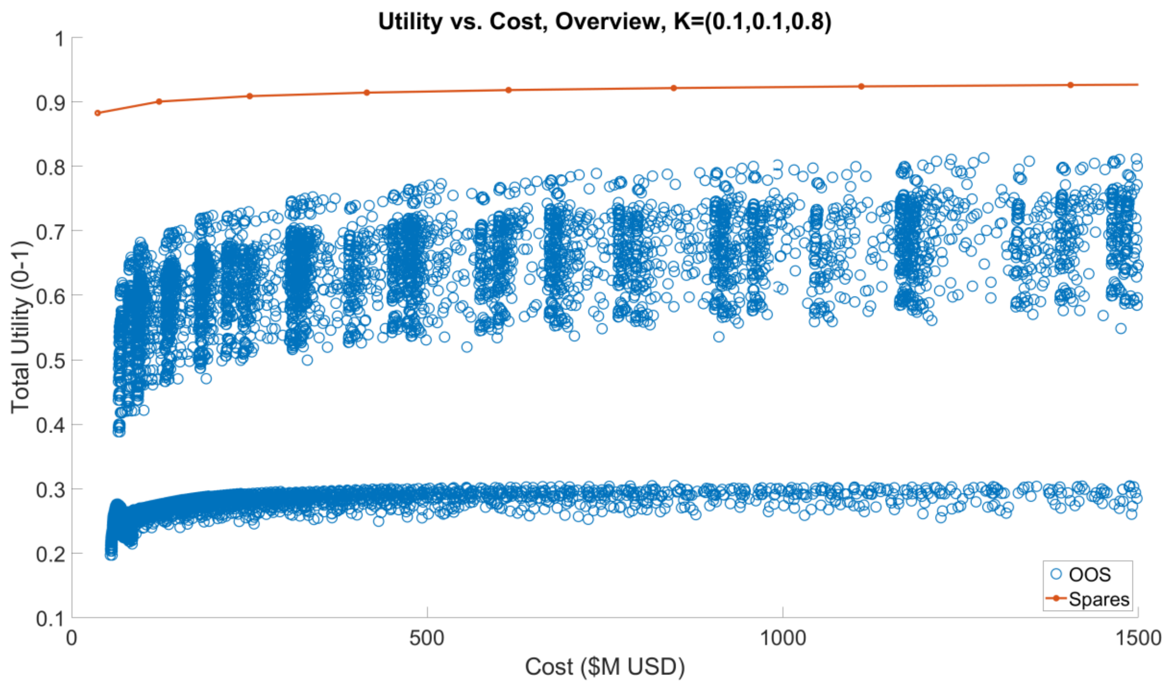

Figure 5-16 Scenario 4 – Tradespace overview

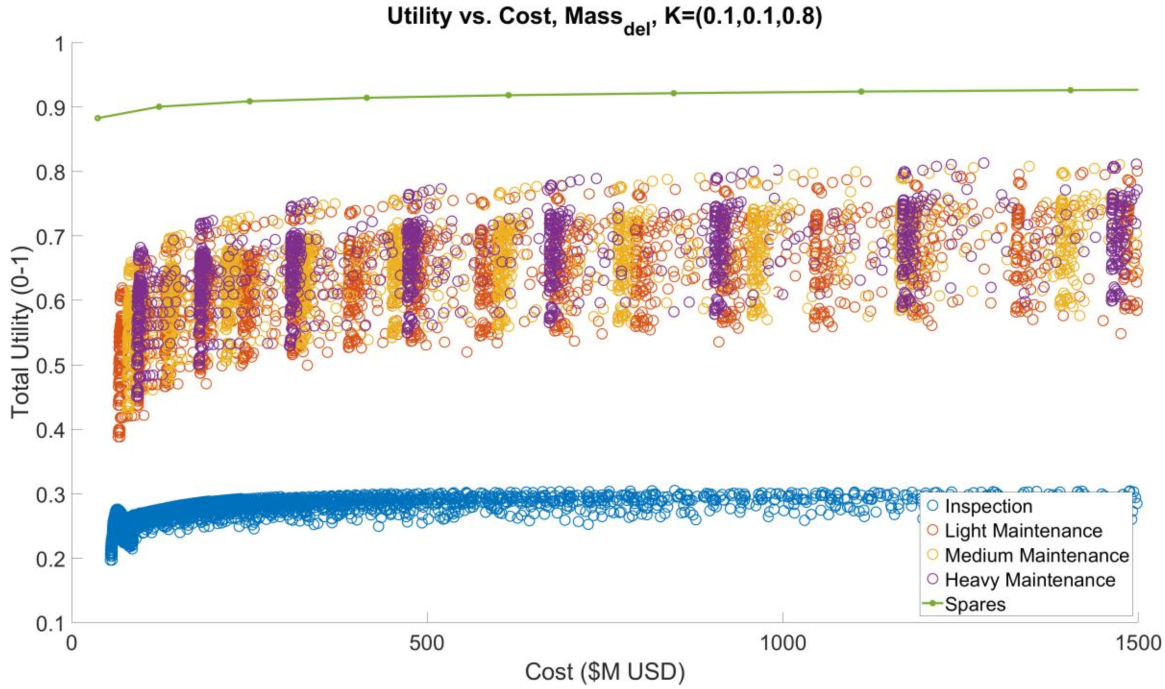

Figure 5-17 Scenario 4 – Comparing mass$_{del}$, servicing type

$$Scenario\ 4 = [k_1 = 0.1,\ k_2 = 0.1,\ k_3 = 0.8]$$

Scenario 4 places all emphasis on the amount of mass delivered to the clients. The orbital spares solution provides the most amount of servicing resources available into the client constellation. However, these resources are not distributed throughout the system. The spares solution provides the greatest utility over all OOS designs as shown in Figure 5-17, the horizontal trends for the other solutions each provide decreasing amounts of servicing mass which we can more clearly see in Figure 5-17.

5.2 Reduction of system requirements and mission assurance

We have generated the framework and results for evaluating a feasible OOS system architecture. The next area to explore is how we can leverage OOS to change the current paradigm of space systems engineering in order to reduce costs and also increase flexibility. We can do this through adjusting the failure rate. We will take the previous failure rate and increase it by 50%, going from 30% to 45%. This increase in failure rate can also be viewed as a reduction in the reliability and mission assurance requirements, this can translate to program cost reductions without the need to have such high system requirements which are prevalent in the aerospace industry. This lowering of the reliability requirements allows us to accept an increase in failure rates, which makes OOS an even more viable option for future flexible solutions and as a means to address failure, risk, and uncertainty.

This acceptance of increased failure rate negatively affects the timeliness metric by penalizing the OOS or spares satellite for not mitigating the failure more quickly as discussed in the timeliness utility of section 4.4.1. However, there is a beneficial reduction in cost of the overall system by reducing the system requirements. Previous papers summarize that reducing design life can reduce overall system costs by 30-40% in certain cases, we provide a discounted system cost of 30% to conservatively estimate the benefit of reducing system requirement.

5.2.1 Scenario 1a – Balanced

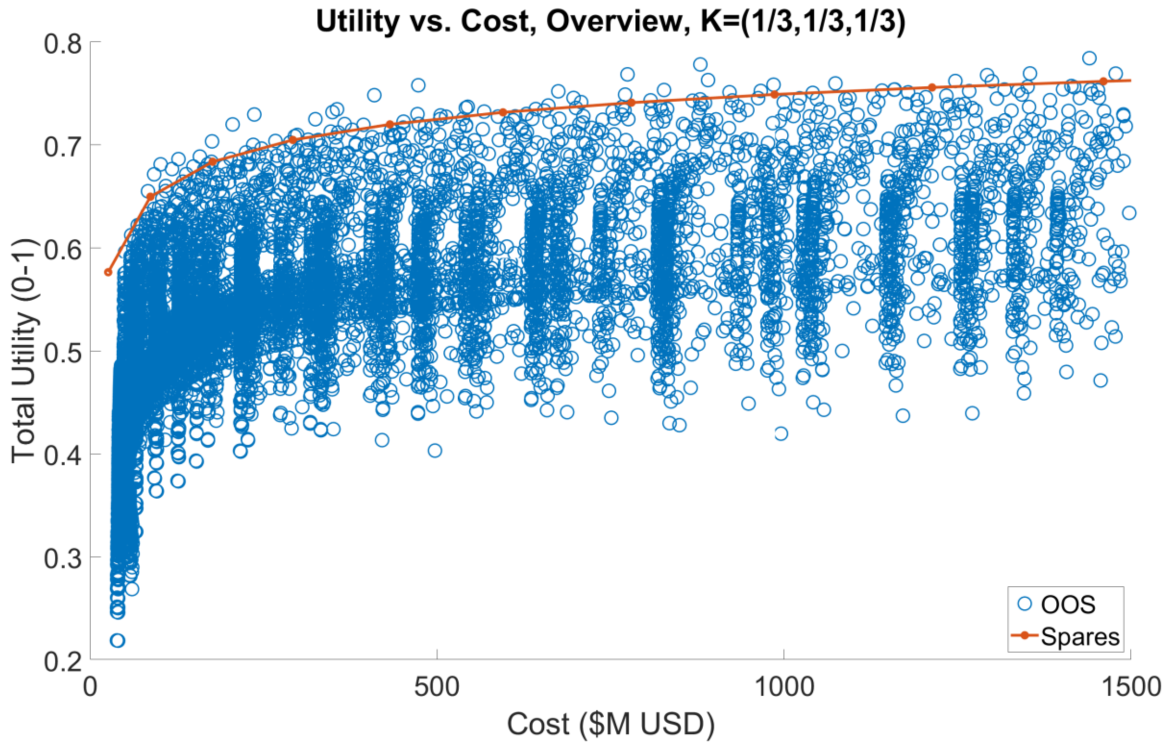

Figure 5-18 Scenario 1a – Overall Tradespace

$$Scenario\ 1a = \left[k_1 = \frac{1}{3},\ k_2 = \frac{1}{3},\ k_3 = \frac{1}{3}\right]$$

By accepting an increased failure, we now have viable OOS solutions for the balanced tradespace of Scenario 1. Previously no OOS solution provided a greater benefit over the spares solution in section 5.1.1. However, there are now viable OOS solutions that outperform the spares solutions in Figure 5-18. The same overall trends regarding phasing ratios, $mass_{del}$, and propulsion type remain the same from Scenario 1.

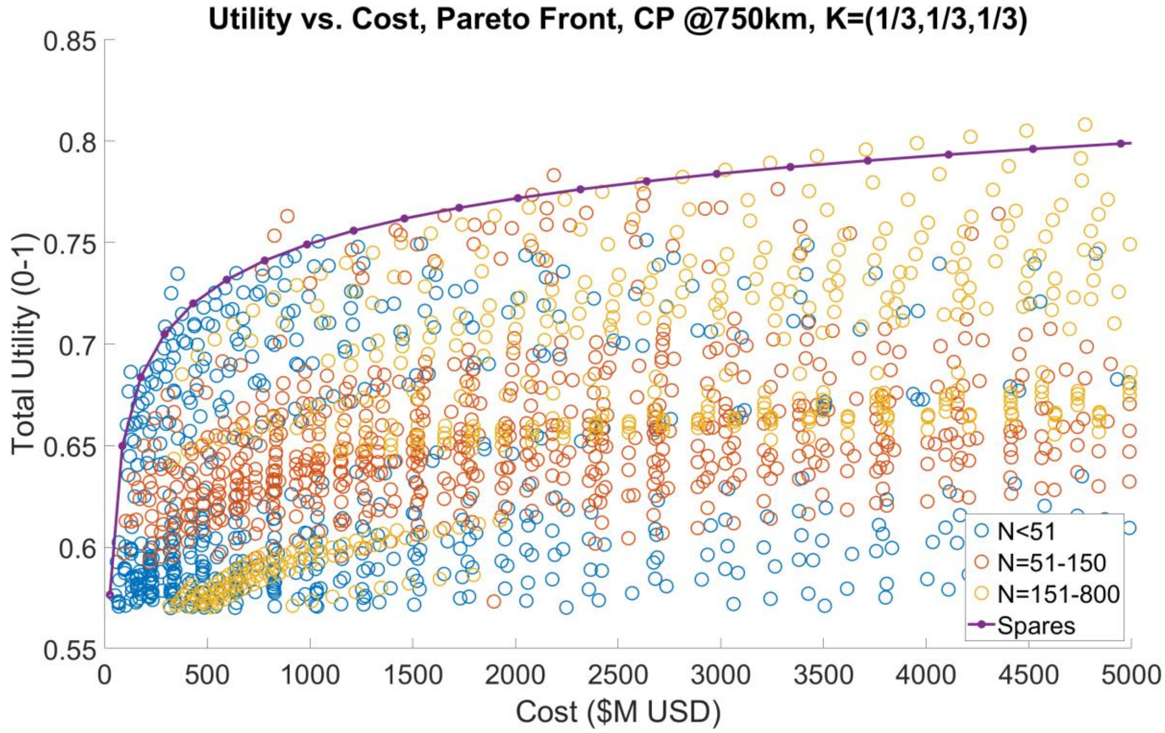

Figure 5-19 Scenario 1a – Analyzing pareto front at 750km by number of clients served, N

One relationship that is more significantly affected by the change in the failure rate is the number of clients serviced, N, which is shown over the pareto front of Figure 5-19. As the constellation grows in size, OOS achieves greater benefits and leverages economies of scale with the increased number of clients being serviced.

5.2.2 Scenario 3a - Quantity

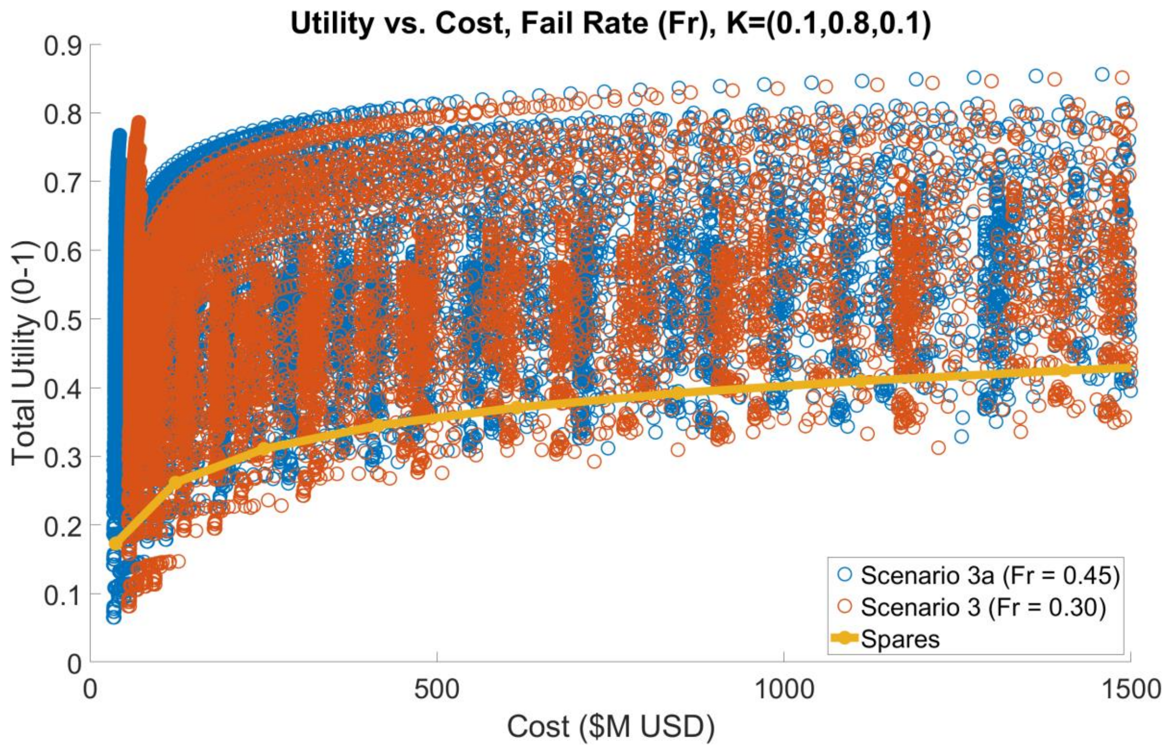

Figure 5-20 Scenario 3a – Comparing failure rates

$$Scenario\ 3a = [k_1 = 0.1,\ k_2 = .8,\ k_3 = .1]$$

In the previous section comparing all the scenarios within the current paradigm of space system architectures, Scenario 3 provided the most desirable situation in which we would want to employ OOS. In Figure 5-20 we compare the original failure rate in Scenario 3 against a possible new paradigm where a higher failure rate is accepted in conjunction with an OOS system which can mitigate and respond to failures.

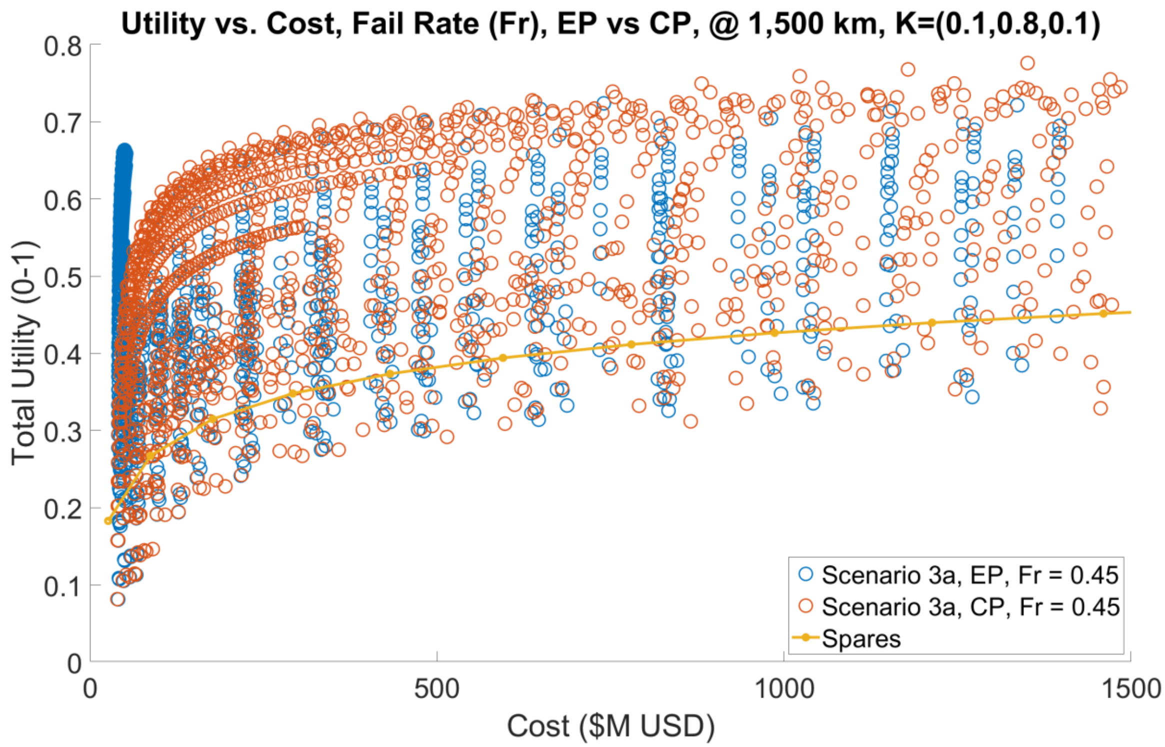

Figure 5-21 Scenario 3a – Comparing EP vs CP

The vertical lines on the left of each graph in Figure 5-20 are the EP solutions which are also highlighted in Figure 5-21, where we show the difference between EP and CP solutions. As stated in 5.1.3, the EP solutions provide a high utility when only visiting or inspecting and delivering no servicing mass. Setting these EP solutions aside, we can look more closely at the benefit of OOS in conjunction with accepting an increase in failure rate.

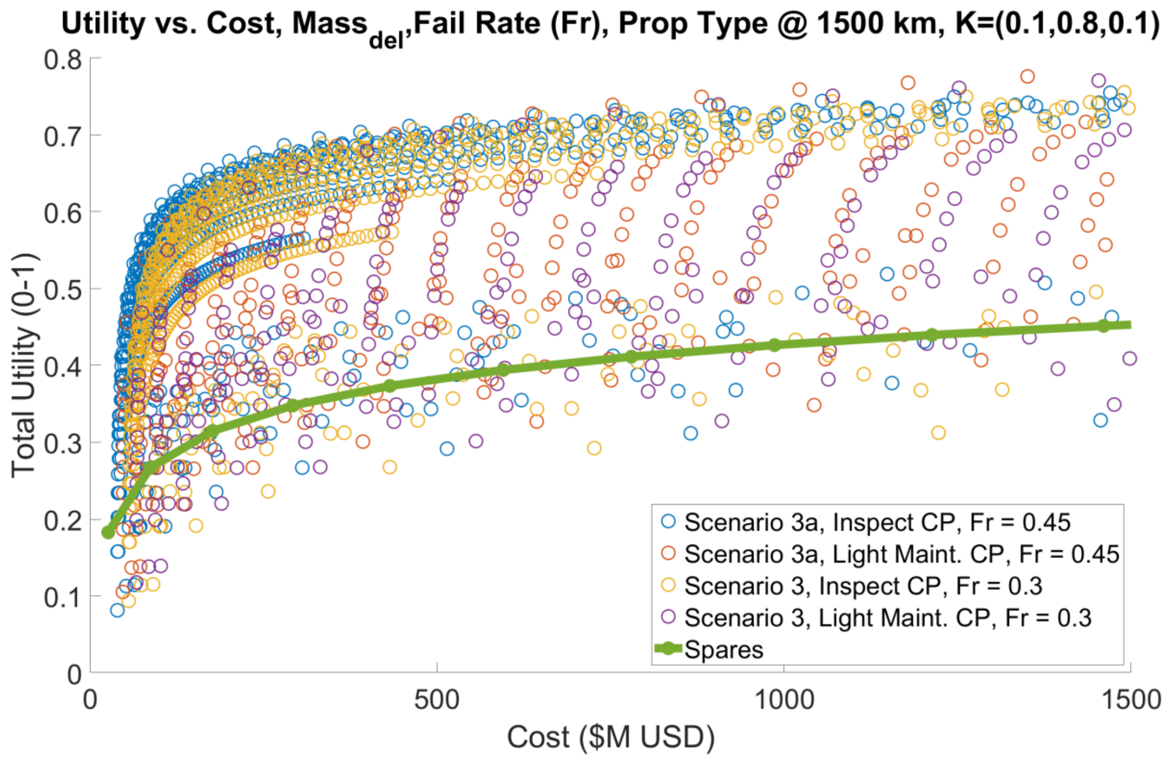

Figure 5-22 Scenario 3a – Comparing mass$_{del}$ and prop type at 1,500 km

In Figure 5-22 we isolate the CP solutions and compare the pareto fronts between Scenario 3 and Scenario 3a. We can see that the OOS solution of 3a performs better than the original despite the increase in failure rate. The increase in failure rate penalizes an OOS if it is not timely in servicing the constellation. Even when delivering servicing mass for light maintenance scenario 3a performs better than the original scenario 3.

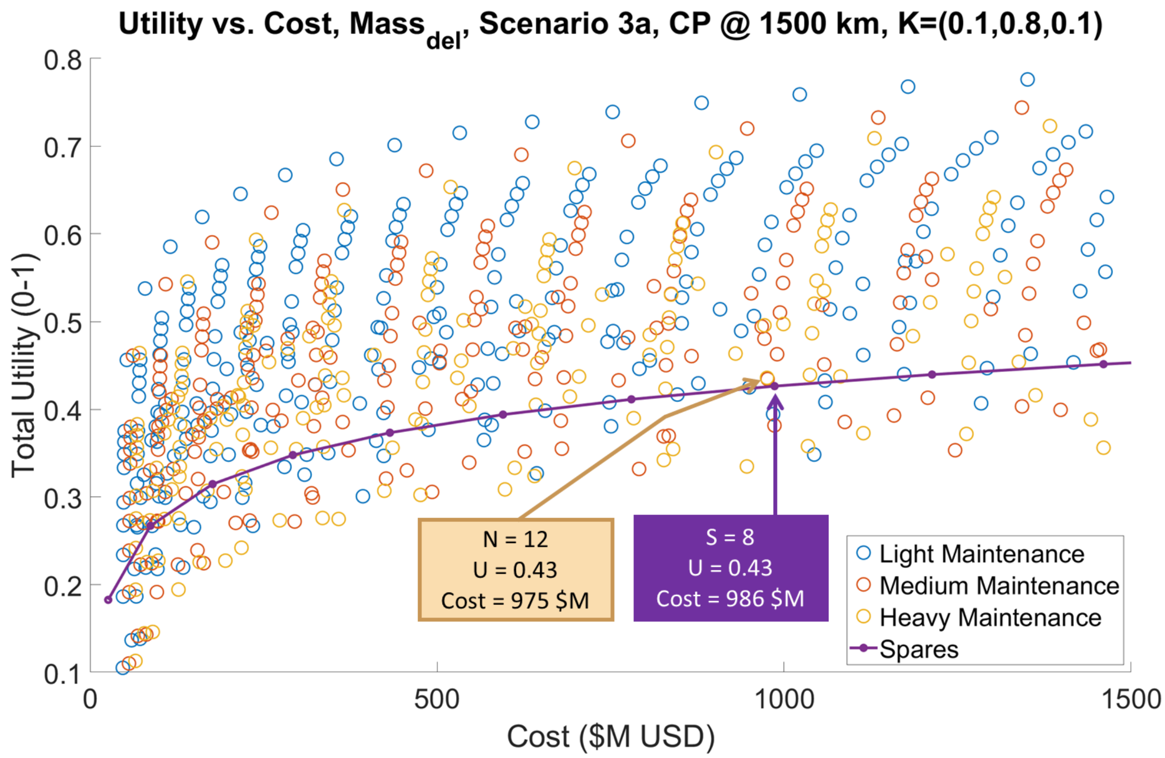

Figure 5-23 Scenario 3a – CP solutions at 1,500 km varying $mass_{del}$

Variable	Description	Scenario 3a	Spares
N	Total number of clients serviced	12	8
$mass_{del\ total}$	Total mass delivered to orbit/client (kg)	10,320	6,880
t	Total servicing time (Days)	143	100
$Cost$	Total Cost ($M)	975	986

Table 5-4 Comparison of OOS and spares solution at S = 6 and $U_{total} = 0.39$

We remove the inspection cases in Figure 5-23 to compare the performance of servicing against the spares alternative. At S = 8, we have a spares solution and an OOS solution with the same $U_{total} = 0.43$ and similar costs, the metrics of each solution are compared in Table 5-4. The OOS solution provides for a higher number of clients serviced and more mass delivered to orbit at the expense of completing taking 43 more days (43%) longer than the spares solution. Additionally, the total mass delivered into the system of the spares solution provides less flexibility to the constellation as more mass is concentrated at fewer orbital positions. This makes OOS more attractive for accepting risk across the constellation and being a more flexible solution.

6. Conclusion

6.1 Summary

Communication constellations are beginning to shift from GEO to LEO. Iridium's LEO communication constellation has paved the way for other providers to enter the market such as SpaceX's Starlink, OneWeb, and Amazon's Kuiper pLEO constellation, which all number in the hundreds to tens of thousands. The rise of pLEO constellations presents unique problems in design life, lifecycle management, replacement, risk reduction, and mission assurance. It also presents new opportunities in leveraging new system architectures.

When a satellite malfunctions or a constellation begins to fail, the only options for clients and satellite operators are to use spare satellites to replace malfunctioning ones or to launch a replacement constellation. OSAM is a rising field and capability that can enable new operations in space. OOS is a subset of OSAM and can provide unique servicing capabilities to inspect, maintain, refuel, repair, upgrade, or relocate client satellites. OOS is a concept that has been under development for several decades and is enabled by advancements in many other space domains. Lessons learned in RPO, autonomy, robotics, and crewed servicing now make autonomous robotic OOS closer to a commercial viability. Recent programs such as Northrop Grumman's MEV show the viability of OOS, at least in GEO. NASA's OSAM-1 will provide further validity and technology feasibility to OOS in LEO. Northrop Grumman's MEP program provides a unique and scalable approach to OOS by leveraging pods.

6.1.1 Limitation of results

Future Uncertainty

This thesis does not incorporate future uncertainty which would affect the parameters and thus results of this analysis. Future space launch costs could decrease resulting in an incentive for the client depending on how much their satellite production costs are in relation to their launch costs. If launch costs are a substantial portion of a pLEO constellation's deployment, then future decreased launch costs may make OOS less attractive. But if the launch costs are only a fraction of the overall pLEO costs, then OOS would be a more desirable option as generating further revenue of existing satellites would provide greater effective returns to the client. If launch costs were to increase then OOS would likely provide greater utility and benefit to clients as increasing the life of existing satellites would be preferential to launching new satellites.

Environmental considerations are not considered in this analysis. Such as space debris and increased risk as more objects are deployed to space. If space debris were to increase as the result of collisions or even just due to congestion of more space objects, this could require satellite operators to be more sustainable and resilient by servicing and maintaining their satellite constellations. Concerns have also arisen due to the environmental sustainability in the atmosphere as pLEO satellites deorbit by the tens of thousands vaporizing hazardous or toxic materials into the atmosphere.

Policy changes by governments and the international community could be imposed for a multitude of reasons to include military purposes, strategic interests, or cooperation. An example of this would be the limitation of future satellite deployments due to exhaustion of radio spectrum issued governed by the International Telecommunication Union (ITU). Since more satellites are being deployed the availability of spectrum has been reduced.

Technological advances are likely in the future which can decrease costs for satellite manufacturers, increase satellite capabilities, or enable more efficient OOS systems. If technology were to drive down costs then pLEO constellation providers may find it cheaper to replace entire constellations. Advancements in payloads for sensing, observation, or communications could drive satellite operators to upgrade their constellations to incorporate capabilities without the desire to rebuild the entire pLEO fleet of satellites. As technology for RPO, sensing, robotics, and autonomy increase OOS becomes more cost effective and feasible. These technological factors can each help or hinder OOS.

RPO

The results from this thesis only represent a future pod solution; a traditional CONOP of carrying all inert mass and necessary servicing resources onboard the servicer is not considered. RPO times are not considered in this thesis but could influence future OOS designs. These RPO times would be dependent on the relationship between the OOS servicer and client satellites if the client was designed for servicing. Preplanned compatible interfaces for servicing could reduce the risk, cost, and time for servicing. Additionally, this RPO time could decrease if the client were executing a cooperative rendezvous with the servicer. Performance and cost results would vary depending on the RPO and interface compatibility between the client and OOS servicing architecture. A non-cooperative servicing mission on client satellites that were not designed to be serviced could provide more significant RPO and docking times. Since RPO and survey of satellites are typically executed over several days and these OOS solutions take years to complete, RPO considerations have a minor effect on these overall results.

Traditional vs. Pod

If the traditional CONOP was used instead of the pod CONOP the relationships and trends would generate similar results as the orbital maneuvers and mass calculations follow the same process. The overall mass required of the OOS system architecture would have been larger creating a higher cost for the same amount of mass being delivered. The OOS servicer would not be able to reach the same number of clients as the it did in the pod CONOP.

6.1.2 Summary of results

Explicit OOS solutions should be designed and optimized for particular client solutions. By leveraging MAUT, a tradespace to explore a general solution is possible to illicit the sensitivities to the performance such as timeliness, number of servicing events, and servicing mass delivered into the client constellation. Timeliness is largely affected by the expected failure rate or design life of the client constellation. A satellite constellation that has a high failure rate would experience more frequent failures and would require more expedient servicing. The number of client satellites being serviced is largely constrained by the time allowed to reach those clients and the speed or TOF at which the OOS can maneuver. The amount of mass delivered into the system also represents the capabilities or resources an OOS can deliver to a client system.

Current Paradigm, Failure Rate = 0.3		
Scenario	Description	Best Option
1	Balanced	Spares
2	Timeliness	Mixed

3	Quantity	OOS
4	Mass delivered	Spares

Table 6-1 Scenario results for current paradigm of system reliability

Changing the weighting for the different attributes for the tradespace allows us to compare the multiple utilities that either a client or commercial servicing provider would be concerned about. Scenario 1 provided an equal balance to each of the three attributes. The remaining attributes allocated 80% of the weighting to a single attribute and a remaining 10% to each of the other two remaining attributes equally. Scenario 2 prioritized the timeliness of service, Scenario 3 prioritized the number of clients serviced, and Scenario 4 prioritized the total mass delivered into the client constellation. These several scenarios and the optimal solutions are provided in Table 6-1. In Scenario 2, spares provided better overall performance at low and high serial production numbers, OOS provided better performance in the middle. Existing space systems have extremely high reliability, system requirements, and mission assurance standards due to an inability to address malfunctions, uncertainty, or emergencies. In the current paradigm of high system reliability in regards to certain scenarios, OOS is viable for some pLEO constellations.

New Paradigm, Accepting higher failure rate, Fr = 0.45		
Scenario	**Description**	**Best Option**
1a	Balanced	OOS
3a	Quantity	OOS

Table 6-2 Tradespace scenario results by increasing failure rate.

We can also facilitate a new paradigm of space system architectures by reducing the system requirements and accepting higher failure rates which can be mitigated by OOS. In Table 6-2 by increasing the anticipated failure rate of constellations by 50% we saw that OOS solutions dominated both in the balanced case and provided greater benefit over the comparative alternatives of using spare satellites.

6.2 Future Work

This thesis provides a framework for assessing the general solution and feasibility for an OOS system architecture for a variety of client constellation configurations for a worst-case scenario with no optimization. In order to determine a more precise answer for the cost-benefit of implementing OOS, one must provide the parameters for a target client constellation to include client dry mass, client wet mass, design life, anticipated failure rate, and orbital parameters (altitude, inclination, RAAN, argument of perigee, eccentricity). Then an OOS system can be designed, evaluated, and optimized to incorporate items not included in this thesis such as scheduling and varying phasing altitudes throughout the mission.

It is also possible to leverage fuel cells to enable higher energy maneuvers by the OOS by leveraging the pod concept to replenish consumable resources on behalf of the servicer. This would provide more flexible options enabling more timely and urgent servicing requests. A higher fidelity EP solution should also be explored to include a more precise analysis on the TOF for that system. Including a more robust failure rate model would be advantageous to exploring new system architectures for reducing system requirements, one that is a function with more continuous results as opposed to a discreet analysis. It would also be useful to incorporate a function that considers overall system performance and uptime; this would likely be a function of outages or communication system unavailability.

Incorporation of future economic, technological, environmental, and political uncertainties should be included in future work to create a more robust OOS solution. OOS provides unique opportunities for the space system architectures. It could be a useful infrastructure system to not just increase revenue for existing satellite constellations, but also to reduce space debris, risk, and negative environmental impacts. Similar to other major infrastructure programs such as the national highway system and GPS, the public could experience significant economic benefit from initial government capital investments to enable future commercial opportunities in OOS space systems.

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