Review of On-Orbit Servicing Considerations for Low-Earth Orbit Constellations

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The field of on-orbit servicing (OOS) has matured to a viable industry through the progression of many technological milestones over the last several decades. Starting from the first orbital rendezvous of Gemini 6 in 1965 to Northrop Grumman's Mission Extension Vehicle successful reposition of Intelsat 901 in 2020, the scientific and engineering achievements have enabled a promising new capability in space. This OOS capability enables higher flexibility, risk reduction, and new expanded system architectures. More recently, the space industry is rapidly deploying a high number of satellites in proliferated low-earth orbit (LEO) constellations at orders of magnitude not seen before. This paper will review enabling technologies, upcoming OOS programs, emerging proliferated constellations, and orbital environmental conditions that enable OOS for potential future clients in LEO. These environmental conditions consist of LEO orbit sensitivities, orbital maneuvers, J2 earth oblateness, and propulsion considerations.

1. Nomenclature

Ω	= longitude of the ascending node (RAAN)
a	= semi-major axis
e	= orbit eccentricity
ω	= argument of perigee
θ	= true anomaly
I	= inclination
V	= velocity
r	= radius
I_{sp}	= seconds of impulse
ΔV	= delta-V
N_p	= number of phasing orbits
t_v	= time in phasing orbit
η	= propulsion system efficiency
β	= characteristic of power system

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2. Introduction

2.1 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 2-1 Types of orbits, not to scale. [7].

2.1.1 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 2-2 and Figure 2-3. 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 2-2 Magnitudes and classification of altitudes of orbits [7]

Figure 2-3 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 2-4 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 2-5. This has enabled many new companies and business models to enter the market [10].

Figure 2-5 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 2-6. High throughput satellites (HTS) are now being deployed to leverage Ka band's higher frequency over Ku band which is illustrated in Figure 2-7. 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 2-6 Phased array antenna example of beam forming [13]

Figure 2-7 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].

2.1.2 What is On-Orbit Servicing?

Figure 2-8 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 2-8. This paper 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 2-9 [21].

Figure 2-9 Estimated demand for In Orbit Servicing (IoS)/OOS [21]

2.1.3 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 2-10 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 2-10 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 2-10 [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 paper exclusively covers robotic and autonomous OOS, crewed missions are not considered.

Figure 2-11 Proposed Hubble Robotic Servicing Mission [25,26]

2.1.4 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 2-12 of an SR-71 Blackbird which was a long-range reconnaissance aircraft.

Figure 2-12 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 2-3. 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 2-13 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 2-13 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 2-14 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.

Satellites		ΔV_{recon}		P_E/P_{max}		Satellites		ΔV_{recon}		P_E/P_{max}	
Reconfigured	Remaining	ΔV	Recon	Static		Reconfigured	Remaining	ΔV	Recon	Static	
1.		318	0.768	0.516		10.		383	0.710	0.684	
2.		197	0.681	0.683		11.		207	0.563	0.487	
3.		397	0.550	0.389		12.		351	0.795	0.433	
4.		384	0.736	0.470		13.		188	0.477	0.398	
5.		121	0.734	0.417		14.		210	0.810	0.430	
6.		176	0.712	0.473		15.		231	0.779	0.700	
7.		271	0.597	0.638		16.		232	0.705	0.508	
8.		229	0.683	0.544		17.		230	0.721	0.497	
9.		364	0.717	0.512		18.		251	0.621	0.592	

Figure 2-14 Example ReCon use case showing how many satellites were reconfigured for 18 randomized global events of interest [29]

2.2 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.

2.3 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 2-15 we see the “Bathtub Curve” which shows some of the considerations for the lifetime of a product or system.

Figure 2-15 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 2-16 we can see the film supply at the bottom and the two recovery vehicles at the top of the satellite.

Major Components of the J-3 System

Figure 2-16 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 2-17 compared to the modern and most recent cockpit in Figure 2-18

Figure 2-17 B-52 Stratofortress cockpit from the 1960s [38]

Figure 2-18 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 2-19. 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	0	0	0	0	0	0	0	0	0	0	0	0
Check all fluids, fill washer solvent.		FREE	0	0	0	0	0	0	0	0	0	0	0	0
Inspect Windshield Wiper Blades		FREE	0	0	0	0	0	0	0	0	0	0	0	0
Check for open recalls		FREE	0	0	0	0	0	0	0	0	0	0	0	0
Replace engine oil and filter conventional	NLOF	\$39.95	0	0	0	0	0	0	0	0	0	0	0	0
Replace engine oil and filter synthetic	NLOFSS	\$54.95	0	0	0	0	0	0	0	0	0	0	0	0
Replace engine oil and filter 5W30 Mobil 1	NLOFS1	\$69.95	0	0	0	0	0	0	0	0	0	0	0	0
Check for any fluid leaks, drive shaft boots		FREE	0	0	0	0	0	0	0	0	0	0	0	0
Check all exterior lighting		FREE	0	0	0	0	0	0	0	0	0	0	0	0
Inspect belts for fraying, excessive cracks		FREE	0	0	0	0	0	0	0	0	0	0	0	0
Inspect / measure tread, adjust pressure & rotate	NROT	\$19.95	0	0	0	0	0	0	0	0	0	0	0	0
Inspect Brake pads, rotors, parking brake, drums & linings.		FREE	0	0	0	0	0	0	0	0	0	0	0	0
Replace a/c In-cabin microfilter	CABIN	\$59.95			0			0			0			0
Replace engine air cleaner filter	AF	\$39.99						0						0
Brake Fluid Exchange	BGCF	\$119.95				0				0				0
Ala Carte Items - not included in Total Price														
Induction Service (Dealer Recommended)	BGINO	\$133.95						0						0
Wheel Balance (Dealer Recommended)	NRBAL	\$44.95			0			0			0			0
Four Wheel Alignment (Dealer Recommended)	NALA4	\$129.95			0		0		0		0		0	
Throttle Body Service (Dealer Recommended)	BGTBS	\$89.95			0			0			0			0
Automatic transmission service (non-CVT)	BGTF	\$199.95						0						0
CVT transmission service		\$219.27												0
Replace Differential oil* (frontier/xterra/titan/armada)	BGDOFF	\$99.95						0						0
Replace Radiator cap		\$29.95						0						0
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

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

Figure 2-19 Example of periodic and preventative maintenance service schedule for Nissan vehicles [40]

2.4 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.

2.5 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.

3. Literature Review

3.1 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 2.1.1 in future constellations. We will summarize the developments of pLEO constellations which are fully operational, partially deployed, and planned.

3.2 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 3-1, 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 3-2 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 3-1 Iridium constellation global view [45]

Figure 3-2 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 3-3 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 3-3 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].

3.3 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 3-4 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 3-4.

Figure 3-5 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 $\sim 53^\circ$ 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 3-5 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° and lower altitudes below -55° degrees are not covered by the Starlink constellation due to the $\sim 53^\circ$ inclination of the Starlink constellation. Similar to the Iridium constellation in Figure 3-1, 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].

3.4 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 3-6 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 3-6.
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 3-6.

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].

GW

China Aerospace Science and Technology Corp. (CASC) filed a spectrum allocation to the International Telecommunication Union (ITU) in September 2020 for 12,992 satellites in LEO between 500-1,145 km in altitude. The constellation is called Guowang (GW). This supports the China's National Development and Reform Commission which lists satellite internet as part of its infrastructure initiatives [78].

3.5 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 3-1 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 3-1, 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].

3.6 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.

3.7 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 [79]. 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 [80]. 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 [81].

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 [81]. 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 [81].

Space Shuttle

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 [82]. 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 [83]. 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	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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. Replaced all six gyroscopes. Replaced a Fine Guidance Sensor (FGS) and the computer. Installed a Voltage/temperature Improvement Kit (VIK). Replaced thermal insulation blankets.
SM3A/STS-103	December 1999	Discovery	<ul style="list-style-type: none"> Replaced the FOC by the Advanced Camera for Surveys (ACS). Revised the NICMOS by installing a closed-cycle cooler. Replaced the solar arrays.
SM3B/STS-109	February 2002	Columbia	<ul style="list-style-type: none"> 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.
SM4/STS-125	May 2009 (Initially planned to conduct in 2003 and then delayed due to Columbia's accident.)	Atlantis	

Table 3-2 Space Shuttle missions to service HST [84]

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 [85]. Details for the HST servicing missions can be seen in Table 3-2. The Space Shuttle also went on to retrieve and service several satellites listed in Table 3-3. 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 [86]. 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 [86]
STS-51-A (STS-19)	November 1984	Discovery	Recover Palapa B2 and Westar 6 satellites due to previous failed deployment [87]
STS-49	May 1992	Endeavour	Serviced perigee kick motor for Intelsat VI and redeployed [88]

Table 3-3 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 [89]. XSS-11 was a follow-on mission of a larger 100 kg satellite which successfully conducted autonomous RPO operations in April 2005 [90].

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 [91]. 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) [92]. 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 [92]. 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 [93]. Intelsat 901's originally was built with a 13 year design and launched in 2001 [94].

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 [95]. 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 [96]. 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 [96]. 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 [97].

3.8 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 [98]. 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 [99].

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 [100].

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 [101]. In December 2020 Lockheed Martin was awarded an additional contract to build the 11th and 12th, GPS Block 3F satellites [101]. 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 [102].

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 [103]. This Kurs plans to upgrade this legacy system with more recent advancements made in machine vision, radar, and robotics to execute autonomous operations [103]. 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 [103].

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 [104]. DARPA has teamed with Space Logistics LLC, a subsidiary of Northrop Grumman, which also operates the MEV program [105]. RSGS is slated to launch in 2023 with servicing of government satellites at a set price and the ability for follow-on commercial opportunities [105].

OSAM-1

NASA has identified a new national initiative for the US space program called On-Orbit Servicing, Assembly and Manufacturing (OSAM), this initiative is supported by two technology demonstration programs called OSAM-1 (formerly called Restore-L) and OSAM-2 [106]. 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) [107]. 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 [108,109].

OSAM-2, formerly known as Archinaut One, is a technology demonstration mission to deploy a solar array in space [106]. 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 [110].

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.

4. OOS System Design Considerations

4.1 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 4-1 and Figure 4-2.

Figure 4-1 Classical orbital elements [30]

Figure 4-2 Classical orbital elements[111]

A satellite orbit is defined by the orbital elements a , e , i , Ω , ω , 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.

4.2 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 4-3. 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 [112,113]. Estimates have ranged up to 6,500 kg as SPIDER was added to the program for a follow-on assembly mission and a deorbiting study was executed by NASA [114]. 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 4-3 Wet Mass vs. relevant OOS missions [112–116]

4.3 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 .

4.4 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} .

$$V_{orbit} = \sqrt{\frac{\mu}{a}} \quad 4-1$$

$$\Delta V_{plane} = 2V_{orbit} \sin\left(\frac{\Delta i}{2}\right) \quad 4-2$$

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 $\Delta \Omega$ change, however this maneuver is still cost prohibitive in LEO.

4.5 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.

$$a_{transfer} = a_0 + a_1 \quad 4-3$$

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

$$\Delta V_{Hohmann} = |V_0 - V_{transfer0}| + |V_1 - V_{transfer1}| \quad 4-5$$

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 $\Delta v = 0$.

$$r_{transfer_apo} = a_0, \quad r_{transfer_peri} = a_1, \quad r_{transfer_peri} > r_{Earth} + 200km \quad 4-6$$

$$\Delta V_{apo} = V_0 - V_{peri} = \sqrt{\frac{\mu}{r_{transfer_peri}}} \left(1 - \sqrt{\frac{2r_{transfer_apo}}{r_{transfer_apo} + r_{transfer_peri}}} \right) \quad 4-7$$

$$\Delta V_{peri} = V_0 - V_{peri} = \sqrt{\frac{\mu}{r_{transfer_apo}}} \left(\sqrt{\frac{2r_{transfer_peri}}{r_{transfer_apo} + r_{transfer_peri}}} - 1 \right) \quad 4-8$$

$$\Delta V_v = \Delta V_{apo} + \Delta V_{peri} \quad 4-9$$

We can also find the time it takes to phase the orbits, t_p , 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, $T_0 - T_1$.

$$T = 2\pi \sqrt{\frac{a^3}{\mu}} \quad 4-10$$

$$\Delta v = |v_0 - v_1| \quad 4-11$$

$$Phasing\ Ratio = \frac{2\pi - \Delta v}{2\pi} \quad 4-12$$

$$N_p = \frac{Phasing\ Ratio\ T_0}{T_0 - T_1} \quad 4-13$$

$$t_v = N_p T_1 \quad 4-14$$

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.

4.6 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 4-4 Earth is an oblate sphere and not a uniform sphere. This oblateness results in the J-2 perturbation in orbital mechanics [117]

Due to the rotation of the Earth centrifugal forces are experienced which causes the Earth to bulge around the equator as seen in Figure 4-4, 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 [111]. 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.

$$\omega = \frac{2\pi}{T} \quad 4-15$$

$$\dot{\Omega} = \frac{3R_E^2 J_2}{2(a(1-e^2))^2} \omega \cos i \quad 4-16$$

4.7 RAAN Change (Ω)

In 2014 Dr. Robert Legge proposed leveraging the J_2 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.

$$\Delta\Omega = \frac{\pi}{planes} \quad 4-17$$

$$\Delta\dot{\Omega} = \dot{\Omega}_1 - \dot{\Omega}_0 \quad 4-18$$

$$t_{\Omega} = \frac{\Delta\Omega}{\Delta\dot{\Omega}} = \frac{\pi(\dot{\Omega}_1 - \dot{\Omega}_0)}{planes} \quad 4-19$$

4.8 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.

4.9 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 [118]. 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.

$$mass_{wet} = mass_{dry} e^{\frac{\Delta V}{g Isp}} \quad 4-20$$

$$mass_{propellant} = mass_{wet} - mass_{dry} = mass_{wet} \left(e^{\frac{\Delta V}{g Isp}} - 1 \right) \quad 4-21$$

4.10 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 [118]. 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 [118].

$$\eta = \frac{P_j}{P_s} \quad 4-22$$

$$F = 2 \frac{\eta P_s}{g Isp} \quad 4-23$$

$$mass_{sa} = \beta P_s \quad 4-24$$

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 4-20. 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, $\eta=0.65$, $g=9.8$ m/s, and $Isp=3100$ seconds which are standard performance characteristics for an EP system [118].

Figure 4-5 Tradespace on Mass of CP vs Mass of EP system

In Figure 4-5 we calculate the difference in mass, $\Delta M = \text{Mass EP} - \text{Mass CP}$, using Eq. 4-20 through **Error! Reference source not found..** 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 [116].

5. Conclusion

5.1 Summary

Motivations and Why Now

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.

pLEO Constellations

Iridium is currently the only pLEO constellation that has been fully deployed with its second generation of satellites fully deployed to orbit. This provides a baseline for analysis of pLEO constellations. SpaceX's Starlink is quickly maturing with estimates of full global coverage being achievable within 2021. Starlink shows great promise and maturity in delivering even more bandwidth and capabilities such as space based broadband internet access over Iridium. OneWeb is the next closest in maturity with their partially deployed constellation but have achieved more polar coverage than Starlink. Amazon's Kuiper constellation is still in its early development stages but seeks to make headway as they are acquiring the licensing and launch vehicles to begin deploying their constellation. Government agencies like the United States' SDA are also in the early stages of developing their own government constellation. Chinese companies have also announced their intention of deploying mega constellations.

Design Considerations

OOS is multi-disciplinary with many coupled design variables. This is amplified in LEO due to the gravity potential compared to larger orbits like GEO. It is beneficial from a cost perspective to be economical for orbital maneuvers in LEO. Impulsive in-plane phasing maneuvers are achievable, but inclination plane changes are prohibitive. However, it is possible to change RAAN by leveraging nodal precession and J2. Both chemical and electric propulsion systems are viable choices for OOS. A chemical propulsion system is desirable for time sensitive or short duration missions, while electrical propulsion systems are desirable for longer duration missions. Since the design variables and choices are coupled in order to determine the utility of OOS in a particular system, explicit analysis should be done for that constellation.

5.2 Future Work

This paper provides a framework for assessing the general considerations of an OOS system architecture for a variety of client constellation configurations. 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 paper such as scheduling and varying phasing altitudes throughout the mission.

In a future paper, we intend to explore a generalized solution for evaluating the cost-utility tradespace for OOS by enumerating across the spectrum of design variables to determine the degree of their sensitivity on the tradespace. Considerations shall consider the utility of a system with respect to timeliness, number of servicing events, and types of servicing. The types of servicing events can range in difficulty from inspection, through routine maintenance, up to heavy invasive robotic servicing.

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.

References

- [1] *Satellite Database* | Union of Concerned Scientists. Cambridge, MA, 2021.
- [2] Cates, G. R., Houston, D. X., Conley, D. G., and Jones, K. L. *Launch Uncertainty: Implications for Large Constellations*. El Segundo, CA, 2018.
- [3] Research, N. S. *NSR Report Forecasts \$4.5 Billion in Cumulative Revenues from In-Orbit Satellite Services by 2028*.
- [4] Hastings, D. E., Putbrese, B. L., and La Tour, P. A. “When Will On-Orbit Servicing Be Part of the Space Enterprise?” *Acta Astronautica*, Vol. 127, 2016, pp. 655–666. <https://doi.org/10.1016/j.actaastro.2016.07.007>.
- [5] Putbrese, B. L. *Exploring Design and Policy Options for Orbital Infrastructure Projects*. 2015.
- [6] Ho, K., Wang, H., DeTrempe, P. A., du Jonchay, T. S., and Tomita, K. “Semi-Analytical Model for Design and Analysis of On-Orbit Servicing Architecture.” *Journal of Spacecraft and Rockets*, 2020, pp. 0–0. <https://doi.org/10.2514/1.A34663>.
- [7] Bagad, V. S. *Satellite Communications*. Technical Publications Pune, 2009.
- [8] Shingo Ohmori, Hiromitsu Wakana, and Seiichiro Kawase. *Mobile Satellite Communications*. Artech House Telecommunications Library, 1997.
- [9] Our Introduction to Iridium. *California Near Space Project*. <http://www.cnspace-inc.com/our-introduction-to-iridium/>. Accessed Apr. 7, 2021.
- [10] Matthews, J. The Decline of Commercial Space Launch Costs. *Deloitte Perspectives*. <https://www2.deloitte.com/us/en/pages/public-sector/articles/commercial-space-launch-cost.html>. Accessed Apr. 7, 2021.
- [11] Roberts, T. G. *Space Launch to Low Earth Orbit: How Much Does It Cost?* 2020.
- [12] Fry, A. J. The Role of Ka-Band Satellite Systems in Delivering Broadband Services. 2015.
- [13] Benson, K. Phased Array Beamforming ICs Simplify Antenna Design. *Analog Dialogue*. <https://www.analog.com/en/analog-dialogue/articles/phased-array-beamforming-ics-simplify-antenna-design.html#>. Accessed Apr. 7, 2021.
- [14] Advantages and Disadvantages L,S,C,X,Ku,K,Ka Frequency Bands. *RF Wireless World*. <https://www.rfwireless-world.com/Terminology/Advantages-and-Disadvantages-of-L-S-C-X-Ku-K-Ka-Frequency-Bands.html>. Accessed Apr. 7, 2021.
- [15] Hollander, S. *Autonomous Space Robotics: Enabling Technologies for Advanced Space Platforms*. 2000.
- [16] Ogilvie, A., Allport, J., Hannah, M., and Lymer, J. “Autonomous Robotic Operations for On-Orbit Satellite Servicing.” *Sensors and Systems for Space Applications II*, Vol. 6958, 2008, p. 695809. <https://doi.org/10.1117/12.784081>.
- [17] Daehnick, C., Klinghoffer, I., Maritz, B., and Wiseman, B. “Large LEO Satellite Constellations: Will It Be Different This Time?” *McKinsey*, 2020.
- [18] Tracy, R., and Mullins, B. “Musk’s SpaceX Looking to Compete for \$16 Billion in Federal Broadband Subsidies.” *The Wall Street Journal*, Mar 12, 2020.
- [19] NASA. “On-Orbit Satellite Servicing Study.” *Project Report - Goddard Space Flight Center*, No. October, 2010, p. 190.
- [20] Boyd, I. D., Buenconsejo, Reina, S., Piskorz, D., Lal, B., Crane, K. W., and De La Rosa Blanco, E. “On-Orbit Manufacturing and Assembly of Spacecraft.” *IDA Paper P-8335, Institute for Defense Analysis, Alexandria, VA*, 2017.
- [21] Bokhari, H. In-Orbit Servicing: Stepping up to the Challenge? *Northern Sky Research*. <https://www.nsr.com/in-orbit-servicing-stepping-up-to-the-challenge/>. Accessed Apr. 7, 2021.

- [22] Saleh, J. H., Hastings, D. E., and Newman, D. J. "Spacecraft Design Lifetime." *Journal of Spacecraft and Rockets*, Vol. 39, No. 2, 2002, pp. 244–257. <https://doi.org/10.2514/2.3806>.
- [23] National Aeronautics and Space Administration. Space Shuttle Era. *NASA*. https://www.nasa.gov/mission_pages/shuttle/flyout/index.html. Accessed Apr. 5, 2021.
- [24] STS-61. *NASA*. <https://science.ksc.nasa.gov/shuttle/missions/sts-61/mission-sts-61.html>. Accessed Apr. 8, 2021.
- [25] Gugliotta, G. "NASA Awards Contracts for Rescue of Hubble." *Washington Post*, Oct 05, 2004.
- [26] Cheung, E. Hubble Robotic Servicing and Deorbit Mission (HRS DM). <https://www.edcheung.com/job/hrsdm/hrsdm.htm>. Accessed Apr. 8, 2021.
- [27] Mellinger, P. S. "Supremacy in the Skies." *Air Force Magazine*, 2016.
- [28] Linear Aerospike SR-71 Experiment (LASRE) Refueling during First Flight. *NASA Dryden Flight Research Center Photo Collection*. <https://airrefuelingarchive.files.wordpress.com/2013/01/srvr.jpeg>. Accessed Apr. 8, 2021.
- [29] Legge, Robert S., J. *Optimization and Valuation of Reconfigurable Satellite Constellations under Uncertainty*. Massachusetts Institute of Technology, 2014.
- [30] Straub, A. N. "Expanded Tradespace Analysis and Operational Considerations for Reconfigurable Satellite Constellations." 2020, p. 131.
- [31] Zidbits. What Is The Most Expensive Object Ever Built? <https://zidbits.com/?p=19>. Accessed Apr. 5, 2021.
- [32] Ballhaus Jr., W. F., Casani, J., Dorfman, S., Gallagher, D., Illingworth, G., Klineberg, J., and Schurr, D. *James Webb Space Telescope (JWST) Independent Comprehensive Review Panel (ICRP)*. 2010.
- [33] Radle, B., and Bradicich, T. What Is Serviceability? *National Instruments*. <https://www.ni.com/en-us/innovations/white-papers/13/what-is-serviceability-.html?nisrc=RSS-accc2040>. Accessed Apr. 9, 2021.
- [34] Central Intelligence Agency. CORONA: America's First Imaging Satellite Program . *CIA*. <https://www.cia.gov/legacy/museum/exhibit/corona-americas-first-imaging-satellite-program/>. Accessed Apr. 5, 2021.
- [35] Foley, T. Corona Comes in From the Cold. *Air Force Magazine*. <https://www.airforcemag.com/article/0995corona/>. Accessed Apr. 5, 2021.
- [36] CORONA Satellite Imagery. *National Reconnaissance Office*. <https://www.nro.gov/History-and-Studies/Center-for-the-Study-of-National-Reconnaissance/The-CORONA-Program/Imagery/>. Accessed Apr. 8, 2021.
- [37] Sander, G. F. "The Incredible 50-Year-Old Plane on the Front Lines of the North Korea Standoff." *Politico*, Jan 20, 2018.
- [38] Cutler, C. 18 Things You Never Knew About The B-52 Stratofortress. *boldmethod*. <https://www.boldmethod.com/blog/lists/2015/05/18-things-you-never-knew-about-the-b-52-stratofotress/>. Accessed Apr. 9, 2021.
- [39] Davies, A. B-52 Bomber Gets Its First New Communications System Since the 1960s | WIRED. *Wired Magazine*, May 22, 2014.
- [40] Maintenance Schedule for Nissan Cars and Trucks 2014-2018. *Nissan Universal*. <https://universal-nissan.com/maintenance-schedule>. Accessed Apr. 9, 2021.
- [41] Northern Sky Research. Satellite EOL: Not One Size Fits All. *NSR*. <https://www.nsr.com/satellite-eol-not-one-size-fits-all/>. Accessed Apr. 5, 2021.
- [42] Burgess, E., Frisbie, J., Jones, M., and Krause, C. *Cost of Mission Assurance for Space Programs*. New Orleans, LA, 2013.

- [43] Iridium NEXT - Satellite Missions. *eoPortal Directory*. <https://directory.eoportal.org/web/eoportal/satellite-missions/i/iridium-next>. Accessed Apr. 13, 2021.
- [44] Graham, W. Iridium NEXT-5 Satellites Ride to Orbit on SpaceX Falcon 9. *NASA Spaceflight*. <https://www.nasaspaceflight.com/2018/03/iridium-next-5-satellites-spacex-falcon-9/>. Accessed Apr. 13, 2021.
- [45] Schweber, B. The Iridium Global Satcom System, Part 2: The Implementation. *Microcontroller Tips*. <https://www.microcontrollertips.com/iridium-global-satcom-system-part-2-implementation-faq/>. Accessed Apr. 13, 2021.
- [46] Iridium Coverage Animation.Gif. *Geometry Center, University of Minnesota*. https://en.wikipedia.org/wiki/File:Iridium_Coverage_Animation.gif. Accessed Apr. 13, 2021.
- [47] Pasztor, A. “Aging Iridium Network Waits for Key Satellite Replacements - WSJ.” *The Wall Street Journal*, Aug 23, 2016.
- [48] Henry, C. “Iridium Would Pay to Deorbit Its 30 Defunct Satellites — for the Right Price.” *SpaceNews*, Dec 30, 2019.
- [49] Iridium Timeline. *Iridium Museum*. <https://www.iridiummuseum.com/timeline/>. Accessed Apr. 13, 2021.
- [50] Celestrak: Iridium 33/Cosmos 2251 Collision. *Celestrak*. <http://celestrak.com/events/collision/>. Accessed Apr. 13, 2021.
- [51] Oleksyn, V. “What a Mess! Experts Ponder Space Junk Problem.” *Associated Press*, Feb 20, 2009.
- [52] Foust, J. “Starlink Failures Highlight Space Sustainability Concerns.” *SpaceNews*, Jul 01, 2019.
- [53] del Portillo, I., Cameron, B. G., and Crawley, E. F. “A Technical Comparison of Three Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband.” *Acta Astronautica*, Vol. 159, No. December 2018, 2019, pp. 123–135. <https://doi.org/10.1016/j.actaastro.2019.03.040>.
- [54] Fernholz, T. “Satellite Internet Is a Space Business Widow-Maker—so Why Does Elon Musk Want In? .” *Quartz*, Nov 19, 2014.
- [55] Winkler, R., Barr, A., and Pasztor, A. “Google Satellite Employee Greg Wyler Leaves Company.” *The Wall Street Journal*, Sep 02, 2014.
- [56] Meissier, D. “WorldVu Satellites Issues RFP for 640 Satellites.” *Parabolic Arc*, Nov 11, 2014.
- [57] Winkler, R. Greg Wyler’s OneWeb Satellite-Internet Company Secures Funding. *The Wall Street Journal*. <https://www.wsj.com/articles/greg-wylers-oneweb-satellite-internet-company-secures-funding-1421278832>. Accessed Apr. 14, 2021.
- [58] Clark, S. “OneWeb Files for Bankruptcy.” *Spaceflight Now*, Mar 30, 2020.
- [59] O’Callaghan, J. “U.K. Government Wins Controversial Bid For Bankrupt Mega Constellation Firm OneWeb.” *Forbes*, Jul 03, 2020.
- [60] “Successful Launch Marks Key Milestone for OneWeb’s ‘Five to 50’ Ambition.” *OneWeb*, Mar 25, 2021.
- [61] “OneWeb Secures Investment From Softbank and Hughes Network System.” *OneWeb*, Jan 15, 2021.
- [62] Live Starlink Satellite Map. *Satellite Map*. <https://satellitemap.space/#>. Accessed Apr. 13, 2021.
- [63] Gates, D. “Elon Musk Touts Launch of ‘SpaceX Seattle.’” *The Seattle Times*, Jan 16, 2015.
- [64] de Selding, P. B. “SpaceX Opening Seattle Plant To Build 4,000 Broadband Sats.” *SpaceNews*, Jan 19, 2015.
- [65] Dortch, M. H. *Application For Approval For Orbital Deployment And Operating Authority for the SpaceX NGSO Satellite System Supplement*, FCC 18-38. 2018.

- [66] Foust, J. "SpaceX Launches Another Set of Starlink Satellites as It Nears Global Coverage." *SpaceNews*, Apr 07, 2021.
- [67] Sullivan, T. P. *Request for Modification of the Authorization for the SpaceX NGSO Satellite System*. 2021.
- [68] Sheetz, M. "SpaceX Valuation Driven by Elon Musk's Starship and Starlink Projects." *CNBC*, Feb 19, 2021.
- [69] de Selding, P. B. "Telesat Prepares Shareholder Payday, Outlines 117-Satellite Constellation." *SpaceNews*, Nov 17, 2016.
- [70] "Telesat Begins Deploying Its Global Low Earth Orbit (LEO) Constellation with Successful Launch of Phase 1 Satellite." *Telesat*, Jan 12, 2018.
- [71] Mohoney, D. "Telefónica Tests Telesat's LEO Satellite Broadband Service." *Space IT Bridge*, Jun 10, 2020.
- [72] Telesat Lightspeed Satellite Specifications Sheet. *Telesat*. https://www.telesat.com/wp-content/uploads/2021/02/Lightspeed_Specifications_Sheet.pdf. Accessed Apr. 14, 2021.
- [73] Dortch, M. H. *Petition for Declaratory Ruling to Grant Access to the U.S. Market for Telesat's NGSO Constellation, FCC 17-147*. 2017.
- [74] Dortch, M. H. *Kuiper Systems, LLC Application for Authority to Deploy and Operate a Ka-Band Non-Geostationary Satellite Orbit System, FCC 20-102*. 2020.
- [75] Koziol, M. "Amazon's Project Kuiper Is More Than the Company's Response to SpaceX." *IEEE Spectrum*, Aug 17, 2020.
- [76] "Blackjack Focuses on Risk Reduction Flights and Simulations to Prepare for Full Demonstration." *DARPA*, May 11, 2020.
- [77] Strout, N. "One Military Space Agency's Plan for 1,000 New Satellites by 2026." *C4ISRNET*, Jan 21, 2020.
- [78] Jones, A. "China Is Developing Plans for a 13,000-Satellite Megaconstellation." *SpaceNews*, Apr 21, 2021.
- [79] Simpkinson, S. H., and Mathews, C. W. *Gemini Program Mission Report - Gemini VII*. 1966.
- [80] Uri, J. "55 Years Ago: Gemini VIII, the First Docking in Space." *NASA Johnson Space Center*, Mar.
- [81] Sorokin, I. V., and Markov, A. V. "Utilization of Space Stations: 1971-2006." *Journal of Spacecraft and Rockets*, Vol. 45, No. 3, 2008. <https://doi.org/10.2514/1.32772>.
- [82] Logsdon, J. M., Williamson, R. A., Launius, R. D., Acker, R. J., Garber, S. J., and Friedman, J. L. *Developing the Space Shuttle*. NASA, 1999.
- [83] King, D. *Space Servicing: Past, Present, and Future*. 2001.
- [84] Li, W. J., Cheng, D. Y., Liu, X. G., Wang, Y. B., Shi, W. H., Tang, Z. X., Gao, F., Zeng, F. M., Chai, H. Y., Luo, W. B., Cong, Q., and Gao, Z. L. "On-Orbit Service (OOS) of Spacecraft: A Review of Engineering Developments." *Progress in Aerospace Sciences*, Vol. 32, No. 120, 2019, p. 120. <https://doi.org/10.1016/j.paerosci.2019.01.004>.
- [85] Dunbar, B. About - Hubble Servicing Missions. *NASA*. https://www.nasa.gov/mission_pages/hubble/servicing/index.html. Accessed Apr. 15, 2021.
- [86] NASA - STS-41C. *NASA John F. Kennedy Space Center*. https://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-41C.html. Accessed Apr. 15, 2021.
- [87] NASA - STS-51A. *NASA John F. Kennedy Space Center*. https://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-51A.html. Accessed Apr. 15, 2021.

- [88] NASA - STS-49. *NASA John F. Kennedy Space Center*. https://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-49.html. Accessed Apr. 15, 2021.
- [89] Davis, T., Baker, T., Belchak, T., and Larsen, W. XSS-10 Micro-Satellite Flight Demonstration Program. 2003.
- [90] AFRL. "XSS-11 Micro Satellite." Vol. 11, 2005.
- [91] Friend, R. B. "Orbital Express Program Summary and Mission Overview." *Sensors and Systems for Space Applications II*, Vol. 6958, No. April 2008, 2008, p. 695803. <https://doi.org/10.1117/12.783792>.
- [92] Dennehy, Cornelius J Carpenter, J. R. *A Summary of the Rendezvous, Proximity Operations, Docking, and Undocking (RPODU) Lessons Learned from the Defense Advanced Research Project Agency (DARPA) Orbital Express (OE) Demonstration System Mission*. 2011.
- [93] Henry, C. "FCC Begins Approval of Orbital ATK Satellite-Servicing Mission for Intelsat-901." *SpaceNews*, Dec 12, 2017.
- [94] Forrester, C. "Satellite 'Space Tug' Gets Approval." *Advanced Television*, Dec 18, 2017.
- [95] "Intelsat 901 Satellite Returns to Service Using Northrop Grumman's Mission Extension Vehicle." *Northrop Grumman*, Apr 17, 2020.
- [96] Rainbow, J. MEV-2 Servicer Successfully Docks to Live Intelsat Satellite. *SpaceNews*. <https://spacenews.com/mev-2-servicer-successfully-docks-to-live-intelsat-satellite/>. Accessed Apr. 19, 2021.
- [97] Foust, J. Satellite Servicing Industry Seeks Interface Standards. *SpaceNews*. <https://spacenews.com/satellite-servicing-industry-seeks-interface-standards/>. Accessed Apr. 19, 2021.
- [98] Mathewson, S. "Tiny Astroscale Satellite Will Test Space Junk Cleanup Tech with Magnets." *Space*, Apr 08, 2021.
- [99] "Astroscale Celebrates Successful Launch of ELSA-D." *Astroscale*, Mar 23, 2021.
- [100] Astroscale Selected as Commercial Partner for JAXA's Commercial Removal of Debris Demonstration Project. *Astroscale*. <https://astroscale.com/astroscale-selected-as-commercial-partner-for-jaxas-commercial-removal-of-debris-demonstration-project/>. Accessed Apr. 19, 2021.
- [101] Erwin, S. Lockheed Martin Gets \$511 Million Contract for Two GPS Satellites. *SpaceNews*. <https://spacenews.com/lockheed-martin-gets-511-million-contract-for-two-gps-satellites/>. Accessed Apr. 19, 2021.
- [102] Erwin, S. "Lockheed Martin to Upgrade GPS Satellites for In-Orbit Servicing." *SpaceNews*, Feb 26, 2021.
- [103] Erwin, S. "Startup Using Soviet-Era Technology to Build Satellite Servicing Vehicle." *SpaceNews*, Mar 10, 2021.
- [104] Robotic Servicing of Geosynchronous Satellites. *DARPA*. <https://www.darpa.mil/program/robotic-servicing-of-geosynchronous-satellites>. Accessed Apr. 19, 2021.
- [105] "Parts Come Together This Year for DARPA's Robotic In-Space Mechanic." *DARPA*, Jul 17, 2020.
- [106] Foust, J. "New Initiative to Promote Satellite Servicing and In-Space Assembly Technologies." *SpaceNews*, Nov 03, 2020.
- [107] Werner, D. Maxar Taps MDA for Robotic Satellite Servicing Technologies. *SpaceNews*. <https://spacenews.com/mda-robotics-for-spider-osam-1/>. Accessed Apr. 19, 2021.
- [108] Henry, C. "Maxar, Post-RSGS, Looks to Dragonfly as Means to Commercialize in-Orbit Robotics." *SpaceNews*, Apr 08, 2019.

- [109] Henry, C. “Maxar Wins \$142 Million NASA Robotics Mission.” *SpaceNews*, Jan 31, 2020.
- [110] On-Orbit Servicing, Assembly, and Manufacturing 2 (OSAM-2). *NASA*. https://www.nasa.gov/mission_pages/tdm/osam-2.html. Accessed Apr. 19, 2021.
- [111] Vallado, D. A. *Fundamentals of Astrodynamics and Applications*. Microcosm Press and Springer, Hawthorne, CA and New York, NY, 2007.
- [112] Ticker, R. Restore-L Mission Information. 1–9. <http://ssco.gsfc.nasa.gov/>. Accessed Sep. 9, 2020.
- [113] Lillie, C. F., and MacEwen, H. A. “In-Space Assembly and Servicing Infrastructures for the Evolvable Space Telescope (EST).” *Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave*, Vol. 9904, No. August 2016, 2016, p. 99041O. <https://doi.org/10.1117/12.2233061>.
- [114] Shoemaker, M. A., Vavrina, M., Gayhlor, D. E., McIntosh, R., Volle, M., and Jacobsohn, J. OSAM-1 Decommissioning Orbit Design. 2020.
- [115] *Orbital Express*. 2007.
- [116] Satellite Missions, A. S. MEV-1 (Mission Extension Vehicle-1) and MEV-2. *eoPortal Directory*. <https://eoportal.org/web/eoportal/satellite-missions/m/mev-1>. Accessed Apr. 23, 2021.
- [117] J2 Perturbation. https://ai-solutions.com/_freelyflyeruniversityguide/j2_perturbation.htm. Accessed Sep. 23, 2020.
- [118] James R. Wertz, Jeffery J. Puschell, D. F. E. *Space Mission Engineering: The New SMAD*. Microcosm Press, 2011.