Factors Affecting Feasibility of Disposal as a Service

Anne Aryadne Bennett(1), Stanley Smeltzer (2), Erin Dale(3) , Darren McKnight(4)

(1) Northrop Grumman Systems Corporation, 45101 Warp Drive, Dulles, VA, 20166, USA, Email: anne.bennett@ngc.com
(2) Northrop Grumman Systems Corporation, 45101 Warp Drive, Dulles, VA, 20166, USA, Email: stanley.smeltzer@ngc.com
(3) LeoLabs, 4795 Meadow Wood Ln, Ste 315, Chantilly, VA, 20151, USA, Email: edale@leolabs.space
(4) LeoLabs, 4795 Meadow Wood Ln, Ste 315, Chantilly, VA, 20151, USA, Email: darren@leolabs.space

ABSTRACT

Increasing use of large constellations in Low Earth Orbit (LEO) poses a risk of substantial orbital debris growth. Establishing economically viable disposal services would enable satellite operators to remove non-functional satellites that are unable to execute disposal, limiting derelict traffic. Now is a key time to assess the viability of assisted disposal due to the acceleration of space traffic and increasing profitability of large constellations, since historically high cost is a major impediment deterring removal of defunct objects. This study sketches out concepts for assessing the interplay between servicing architectures and large constellations. This provides insight on potential feasibility of various assisted disposal offerings, and how that may evolve over time due to a variety of factors influencing usage rates. The combination of specific architecture capabilities and disposal service usage rates helps inform understanding of the relationship between rate of use and cost of service as the space economy evolves.

1 INTRODUCTION

The ever-increasing activity in the near-Earth space environment and proliferation of satellites in LEO continue to spark investigations and debate regarding necessary updates to operational practices due to the growing population of space objects. Accelerating this LEO proliferation is the usage and popularity of large constellations which can contain hundreds to thousands of satellites [1]. With this growing population of objects, the number of derelict or non-functional spacecraft and space debris grows as well. In 1978, Donald Kessler suggested the potential for a cascading effect of debris growth that could occur due to collisions between space objects in the LEO environment, known as Kessler Syndrome [2]. More recent research has highlighted the issues with concentrations or “clusters” of derelict objects in higher orbits, where the objects persist for decades to centuries, building up to a significant chance of collision between derelicts over time [3].

While active satellites can maneuver to avoid tracked objects, there is a serious risk of increasing danger from lethal non-trackable (LNT) debris. Various satellites have sustained damage by debris objects that are too small to track but still large enough to damage satellites [4, 5]. A few major collision events have occurred in the LEO environment [6], each of which substantially increased the population of LNT debris, especially when the collision occurred at higher orbits where the debris persists. This debris risk growth will continue to be realized in the event additional breakups, failures, or collisions occur, and the resultant LNT debris population would present a significant threat to active satellites. Increasing populations of non-operational satellites accumulate excessive derelict debris traffic which jeopardizes long-term space safety, as the likelihood that two uncontrolled defunct objects collide increases with increasing derelict traffic. This growing debris population continues to increase the probability that major collisions occur between defunct satellites, increasing the need to remove defunct satellites from orbit.

The space community has been discussing the potential use of satellite servicing, assisted disposal services [7], and even the introduction of Active Debris Removal (ADR) insurance in response to the debris accumulation. These practices can potentially ensure failed satellites do not continue to accumulate, thus mitigating excessive traffic and collision probabilities. Satellite servicing in geostationary orbit (GEO) has been successfully performed since 2020 by Northrop Grumman’s two Mission Extension Vehicles (MEVs) [8]; while additional capabilities, the Mission Robotic Vehicle (MRV) and Mission Extension Pods (MEPs), are on the way [9].

However, the GEO servicing market has many dynamics that are very different from LEO, both in terms of physical requirements and business needs. GEO satellites tend to be more expensive and have longer lifetimes than most assets in LEO. Second, satellite populations in GEO have much lower inclinations and slower velocities, making the LEO environment significantly more difficult for a servicer to maneuver around. Third, the cost-to-

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orbit for LEO constellations is much less expensive than in GEO, making replacement of LEO assets generally more cost effective than conducting servicing. These LEO constellation practices lead to cheaper satellites with shorter lifetimes driving proliferation of LEO and increased debris accumulation. Subsequently, LEO is more congested with derelict objects than GEO. For example, one debris cluster at approximately 975 km, also known as C975, exemplifies this debris accumulation with conjunction models predicting the probability of collision between debris objects to be approximately 26% by 2029 [10]**.**

To combat the growing debris accumulation, international organizations developed guidelines for space debris mitigation in the early 2000s. The Inter-Agency Space Debris Coordination Committee (IADC) submitted findings to be included in the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space which established best practices in the LEO environment [11]. The U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) were developed in 2001 and updated in 2019, providing a key contribution to orbital debris mitigation guidelines within the United States [12]. However, historically there have been extensive issues regarding compliance with these policies due to the lack of strict enforcement or legal authority, with effectively no penalties for non-compliance. Also, the policies were crafted with assumptions and modelling based on heritage launch and traffic rates; the effect of large constellations with rapidly refreshed technology present a very different dynamic.

An example of derelict growth can be seen with a hypothetical 500 satellite constellation at a 900 km altitude. Assuming these satellites have a lifetime of about 5 years and are replaced at this cadence, this would result in the need to replace 100 satellites per year. Compliance with the 25-year disposal rule can be achieved by adjusting to an elliptical orbit with a perigee a little over 400 km and an apogee just under 900km and then passivating to allow re-entry after 25 years. Assuming perfect compliance, this modest constellation would accumulate 2,000 derelict objects in 20 years which would accumulate before even the first set of disposed objects have re-entered. For context, the primary clustered population driving the 26% probability of collision by 2029 in C975 consists of less than 300 tightly clustered objects, with an additional 500 or so transiting through their orbit. The accumulation of 2,000 derelicts which transit most of LEO stemming from a modest 500-satellite constellation that is **perfectly compliant** with existing guidelines is rather concerning.

This example highlights that even if all space traffic management safeguards in place today were successfully enforced and perfectly executed, the increased probability of collision between derelict objects would be substantial. Therefore, these legacy practices are not practical when moving towards larger constellations of thousands of satellites. The combination of the increased derelict-on-derelict collision probabilities and the potential of failed satellites within these constellations is poised to develop into major flight safety implications within the LEO environment in the near-term. The derelicts themselves can be avoided by active satellites, but when they collide, the ensuing hazardous non-trackable debris presents a serious and unmitigable near-term increase in risk to satellites in the region, increasing the rate of satellite failures and derelict traffic accumulation, and accelerating the long-feared “Kessler Syndrome.”

Several lines of effort are being investigated to mitigate these potential near-term flight safety risks. Continued “best practices” documents are being created [13] especially focused on how to operate large constellations so that the benefits of utilizing these large constellations can be realized. Increased modelling accounting for these changes in operational practices is shedding light on appropriate activities to maintain flight safety in the presence of large constellations [14]. Additionally, the usage of assisted disposal, where a non-functional satellite can be removed from orbit by another satellite, is being considered by the community [7]. Given the expense of these missions, a key question is how to render these practices economically viable for operators of large constellations.

Historically, high costs have been a major impediment to the usage of satellite servicing and/or assisted disposal. However, with satellite production and launch costs decreasing, the profitability of these large constellations is very promising [15]. Commercial practices can likely be updated to fly this many satellites effectively and safely, to include improved disposal practices, while still maintaining a healthy business. While there have been concerns that additional requirements could potentially stifle innovation, it is important to consider recent research involving the impact major constellations have on the environment relative to smaller entrants. Improving the reliability and timelines for disposal for just the large constellations has a significant positive impact on the environment [14]; “one-size-fits-all” solutions are not necessarily advisable to optimize the safe use of space. Therefore, it may make sense to consider primarily large constellations for tighter requirements on disposal compliance and timelines. A large constellation should have a large revenue stream, which would allow tightening of operational practices while maintaining a healthy business.

The space community is working collectively to identify solutions to these issues. This paper offers ideas for potential mission profiles and their practicality in light of the numerous factors influencing this problem space. The goal of this research is to consider both simple, near-term, and more complex mission architectures to perform assisted disposal services for LEO satellites and develop methods to assess their projected rates of use. The concept of operations (CONOPS) of three potential mission architectures, near-term (Figure 1), medium-term (Figure 2), and long-term (Figure 3), are developed. These architectures are then assessed to identify the "reachability" in LEO, the area where a single mission could potentially provide service. This couples with projections of LEO populations and estimated rates of satellites requiring disposal services to assess the number of LEO vehicles these mission architectures could potentially service.

Methods to project the future LEO vehicle population, specifically constellations, are developed in parallel with expected rates of vehicles needing servicing. These methods provide understanding into how many vehicles are present in the LEO environment along with their orbital parameters. Utilizing the LeoLabs Short-term LEO Population (SLP) model, this information is modeled over time to assess the expected evolution of the LEO active population. Those results are then coupled with the rates of expected servicing needs by estimating rates of debris-related failures and rates of failures from non-debris causes to understand the evolution of the serviceable population.

Utilizing the reachability analysis, population projections, and failure rate investigation, the number of vehicles needing service that are reachable by each architecture is found. This intersection of information is used to identify when LEO populations may be able to leverage higher rates of service which would ultimately drive down the cost per service. A design reference mission showing the execution of a mission servicing several clients is presented and additional considerations are discussed. The rate of service use will be dependent on many factors; this paper is intended as a point of departure to sketch out concepts for how servicing missions can interact with future LEO populations, parametrically trade key variables, and discuss other important factors influencing potential rates of use.

2 DEVELOPMENTS

2.1 Architectures and Reachability

2.1.1 Potential Architectures

The potential architectures presented below are intended to serve as a point of departure for this thought experiment. There are an infinite number of configurations and design options for these architectures. For the sake of this study, three concepts for mission architectures with increasing complexity are presented and used as discussion points.

A simplistic and near-term architecture uses a small servicer to remove a single object. Increasing in complexity, a larger servicer could remove, refuel, and/or install assisted disposal devices on multiple objects. The third mission architecture, further increasing in scale and complexity, investigates a multi-servicer architecture that is able to serve as a refueler and a rideshare depot for free-flying servicers. This mission architecture would be capable of servicing multiple constellations over different inclination-matched orbital shells and conduct ADR for older derelict populations. During discussions of the three different mission architectures, the term "servicer" is used to denote the satellite performing servicing, while the "client" is used to denote a satellite or debris object in need of servicing. Note that the architectures described in this study are illustrative concepts; Northrop Grumman has mature product lines and competencies that could be leveraged for continued developments.

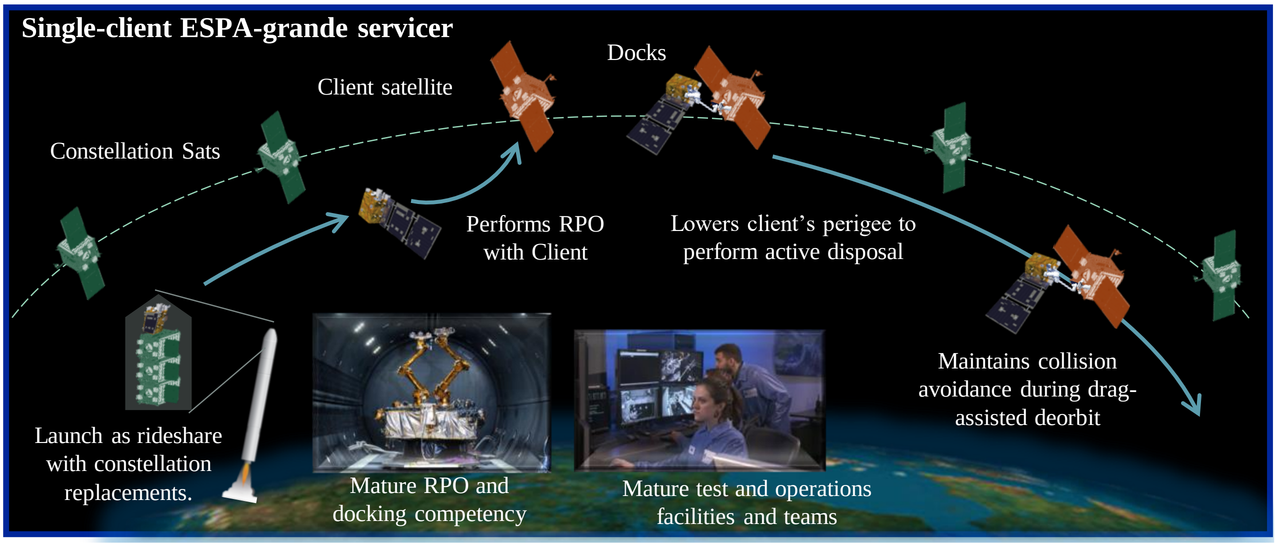

Figure 1. Concept of operations for a simple and near-term architecture, where a single servicer assists a single client vehicle with its disposal

Single-Client Servicer

The simple, single-client servicer mission architecture utilizes an ESPA-Grande class freeflyer as shown in Figure 1. This servicer launches as part of a rideshare with replacement satellites near a non-functional client. The servicer then performs rendezvous and proximity operations (RPO) and captures the client vehicle. Some large constellation operators have discussed using a pre-emplaced docking mechanism [16], which would help to reduce the complexity of hardware required for docking. Upon capture, the servicer lowers the perigee of the client to conduct "active disposal". The servicer maintains its manoeuvring capabilities until lifetime is very short, using an elliptical orbit to leverage drag to reduce the apogee and reduce the total delta-velocity (DV) required. Due to the client vehicle's lower mass (~500 kg), the client vehicle is assumed to be demisable and does not require a controlled re-entry as it burns up in the atmosphere.

Multi-Client Servicer

The multi-client servicer increases the mission architecture complexity by utilizing a ~2,000 kg servicer with hybrid propulsion, as shown in Figure 2. This vehicle would deploy to a region with several client satellites at closely matched inclinations, as discussed in more detail in Section 2.2.1. Once this large servicer reaches the targeted orbit, it would be capable of installing disposal pods and/or drag sails on non-functional satellite(s) and performing refuelling of nearby functional satellites to extend their operational life. This servicer has the capability to increase and decrease its altitude as well as utilize RAAN drift to move between planes that are reasonably close together [17]. This flexibility to span various altitudes and small variations in planes allows this architecture to have a large service footprint, increasing the reachability across multiple constellations. At the end of the servicer's mission, a final derelict object can be captured and disposed with the servicer as it performs its end of mission disposal manoeuvres.

Multi-Plane Servicer

The most complex mission architecture for this study is composed of an ESPAStar with up to six freeflying payloads launching into a densely populated region to access several planes at similar inclinations as shown in Figure 3. Once the ESPAStar reaches a plane where satellites in a constellation need service, it drops off a freeflyer which can carry accoutrements like disposal pods and/or drag sails. The ESPAStar can provide refuelling for the freeflyers [18] and supply additional disposal pods, and/or refuel client satellites, before manoeuvring to the next plane that contains additional

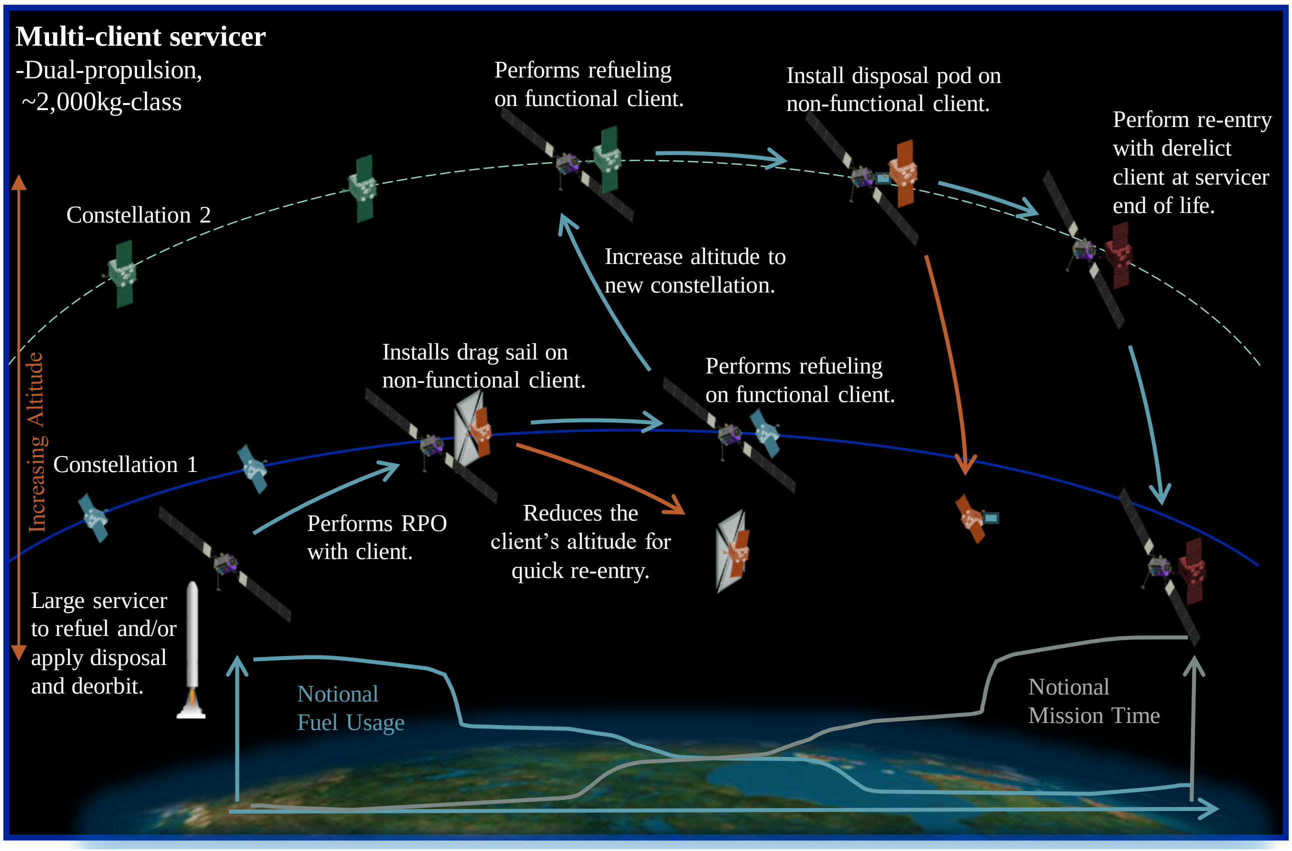

Figure 2. A larger servicer with hybrid propulsion can provide service to several clients in nearby planes

serviceable vehicles. These freeflyers can perform servicing on multiple satellites within a plane utilizing either drag sails for lower-altitude satellites or disposal pods for higher-altitude satellites. Freeflyers could have the capability to be refuelled by the ESPAStar or to obtain additional disposal pods or drag sails from the ESPAStar, thereby extending the freeflyers' mission life to execute multiple servicing procedures. When the ESPAStar reaches the next plane, the next freeflyer is dropped off to service satellites in that plane. This sequence of manoeuvring to desired planes and releasing freeflyers that perform servicing operations for client satellites is repeated until all the ESPAStar's payloads have been expended. At the end of the ESPAStar's mission life, the ESPAStar could leverage its remaining DV and higher thrust capacity to perform active debris remediation on a large derelict object which requires controlled re-entry.

2.1.2 Mapping Reachability

For a single-client servicer, the population of serviceable clients is trivial: the mission is launched to a location such that it can rendezvous with and service the client vehicle. However, multi-client missions become more complex. For a single mission delivering services to multiple client vehicles, the client vehicles must be in close enough proximity to allow the servicer to maneuver from one to the other to the next throughout the mission. For assisted disposal services, it is somewhat unlikely (though not impossible) that several satellites within a single plane would fail, so the DV cost to move from one client to the next is of paramount importance when assessing the feasibility of multi-client servicing missions in LEO. Maneuvering up and down in altitude takes a non-trivial amount of DV, but it pales in comparison to the exorbitant DV cost of plane change maneuvers in LEO. However, differential nodal precession can be used, as described in more detail in [17], to change the right ascension of the ascending node (RAAN) passively leveraging the differential effects of the J2 perturbation on objects at different altitudes. When the servicer is at a different altitude from the client satellite, the RAAN of each satellite will precess at different rates. This allows the servicer to move between clients at different RAANs at a cost of mission time by simply raising or lowering to a different altitude. The servicer waits until the RAAN with the client is aligned and then maneuvers to change altitude and match orbits with the client. Therefore, by spending a combination of DV and mission time, a

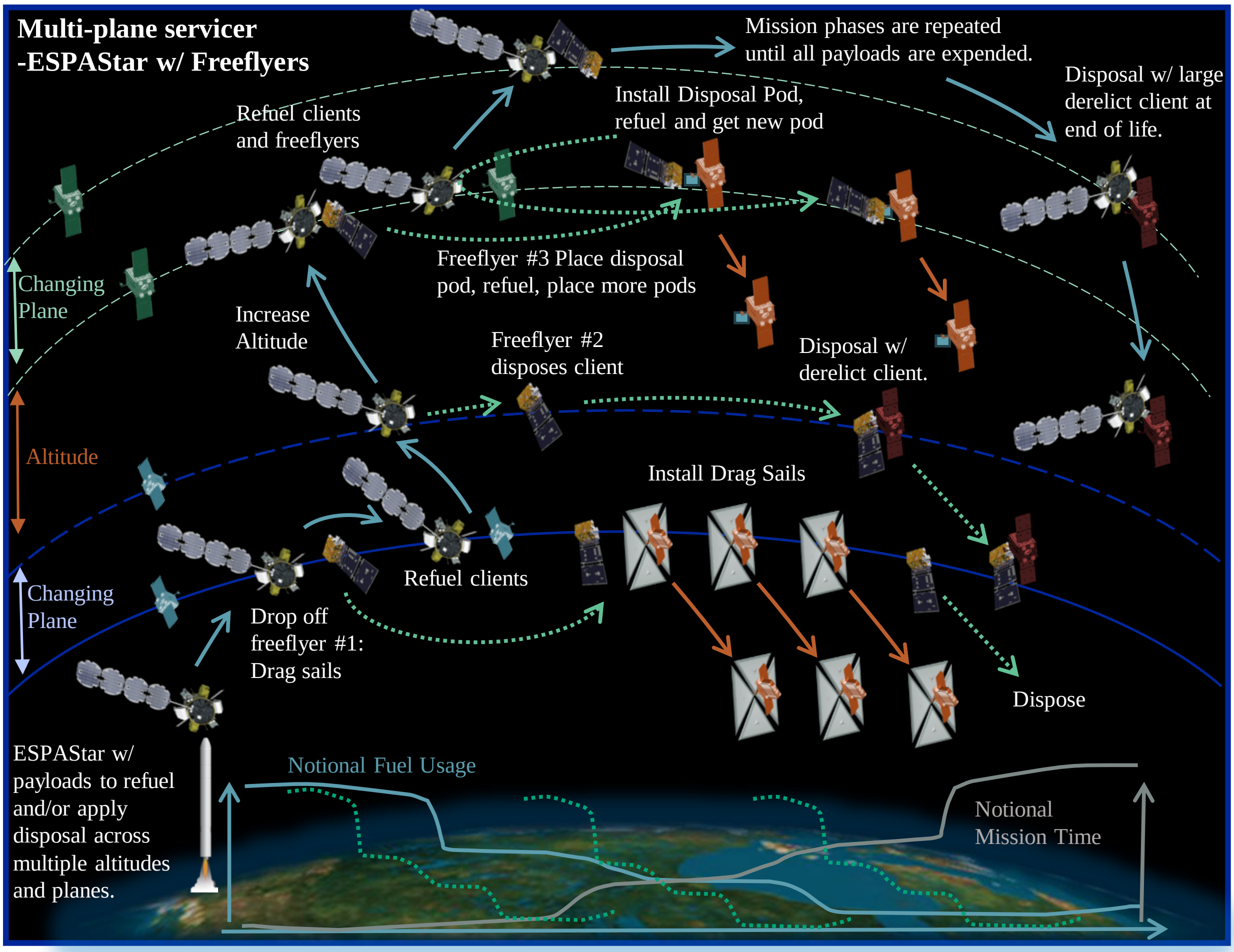

Figure 3. A large servicer with fly-away payloads enables significantly more clients to be serviced per mission

servicer with electric propulsion and ample fuel allows a high DV budget, such that the servicer is able to reach a significant segment of LEO. Inclination changes are limited to small adjustments, but a large swath of altitude and RAAN can be reached by a single servicing mission.

For the purposes of this study, the DV analysis uses a preliminary first-order approach to sketch out the intersection between mission architectures and client populations in LEO. This analysis uses several approximations to develop DV budgets, linearizing portions of the problem, estimating some parameters, and patching together trajectories instead of optimizing flight profiles. Optimizations for EP maneuvers have extensive study in the literature, but for the purposes of this assessment the analysis is kept straightforward to explore the problem space efficiently with adequate accuracy, rather than to comprehensively assess the precise potential mission performance.

To accomplish this three types of maneuvers are defined and first-order methods to estimate the DV and time involved in these maneuvers are employed.

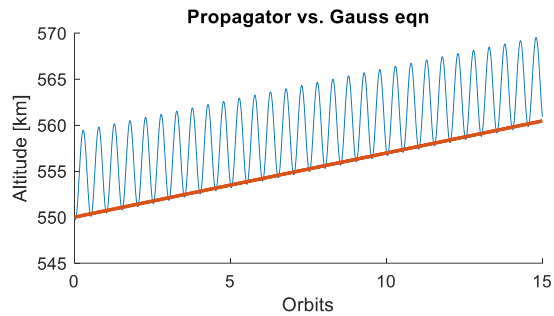

Figure 4. Comparing propagator with EP applied as an acceleration (blue) to the estimated DV to using Gauss's variational equation for semimajor axis (red)

Raise/Lower Altitude: To raise and lower the altitude of a nominally circular orbit, Gauss's variational equation for change in semimajor axis is used, leveraging the formulation in Schaub and Junkins [19, pg. 630]. This formula is linearized in 10 km segments as the orbit is raised and lowered, and the acceleration applied times the time over which it is applied is substituted in to obtain the estimated DV for the 10 km altitude segment. To validate this approach, electric propulsion is added to an orbit propagator incorporating J2, J3, and drag along with two-body mechanics, with the acceleration from the electric propulsion applied as a constant using the estimated vehicle mass at the beginning of the 10 km altitude segment (Figure 4). The direction of the acceleration is along the orbital velocity vector. To calculate the expended fuel, Tsiolkovsky's rocket equation is used to calculate the expended mass to obtain the calculated DV, and then the mass of the vehicle is updated for the next segment. The mission time required to apply each segment of acceleration to affect the 10 km change in altitude is also catalogued.

Change in Inclination: To adjust the inclination a similar approach is used where Schaub's formulation [19] of Gauss's variational equation for inclination is manipulated to identify the relationship between DV and change in inclination as a function of circular orbit altitude. Unsurprisingly, this relationship reduces to a small angle approximation when the out-of-plane thrust to attain the change in inclination is applied primarily near the nodes. For this analysis, a 10% duty cycle is used, meaning the thrust is applied for 2.5% of the (circular) orbit before and after each node, with the direction flipping at each node to apply a consistent change in inclination. The linearized formula is applied in 0.1 deg. segments of inclination change, tallying up the applied DV and elapsed time for the mission budgets. Note the timescale (in orbits) in the x-axis of Figure 5, indicating the extensive time required to change inclination given the 10% duty cycle and significant DV required.

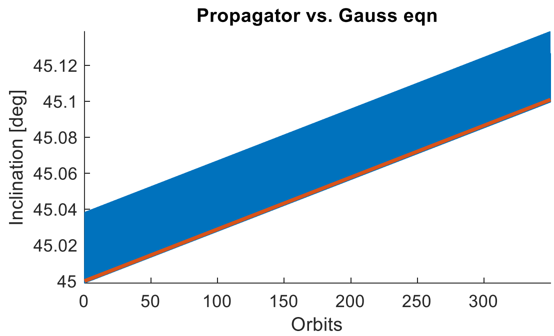

Figure 5. Comparing propagator (blue) to equation (red) for a small change in inclination

Changing RAAN via differential nodal precession: To change the RAAN, the altitude of the servicer must be different from the altitude of the client, such that J2 causes the RAAN of one vehicle to drift at a different rate than the RAAN of the other vehicle. The rate of RAAN drift for a given satellite is calculated via Eq. 1:

$$\frac{d\Omega}{dt} = \frac{-3}{2} J_2 \left(\frac{R_E}{a(1-e^2)}\right)^2 \sqrt{\frac{\mu_E}{a^3}} \cos(i) \qquad (1)$$

This equation is assessed for an array of altitudes to establish the differential rate between these altitudes and the "default" altitude, to assess the amount of drift time required to obtain certain changes in RAAN. Note the dependence on inclination, the RAAN drift rate is higher at lower inclinations and lessens at higher inclinations. Figure 6 illustrates some example RAAN drift times.

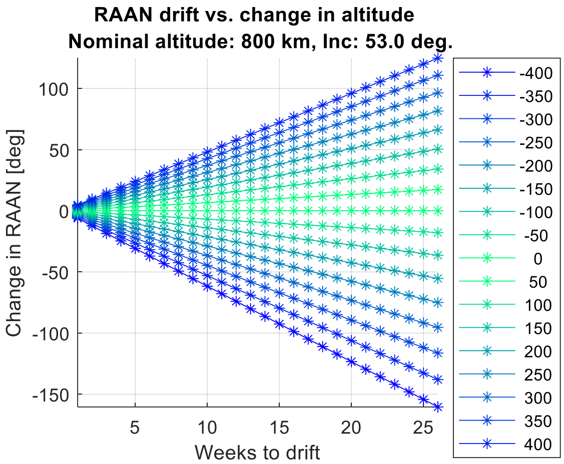

Figure 6. Plotting the change in RAAN over time for various changes in altitude relative to a nominal orbit.

Proximity operations and docking: For proximity operations and docking, a constant amount of DV is bookkept, with the DV reflecting a conservative estimate based on operations.

2.2 Mapping Projected Service Population

2.2.1 Overall LEO Population

Growth over time via Short-term LEO Model

This study leverages the LeoLabs model for assessing projected LEO populations. The short-term LEO population (SLP) model uses trends from the past ten years to project future space object populations five (with high confidence) to 15 (with moderate confidence) years into the future [10]. The paper introduces primary and secondary growth effects for payloads, rocket bodies, and fragments. This model uses the values from 2025 – 2035 to represent the expansive global growth of operational payloads in LEO. Forecasting the growth in the population of operational satellites is difficult given delays in technical development, financing, launch availability, licensing, and other factors. Deployments typically ramp up from a few initial satellites to test and demonstrate the feasibility of the system on orbit to a rapid scaling of launches to populate the system within a set time in accordance with licensing requirements. However, the count of launched payloads does not represent the evolution of operational payloads in orbit per year, as payloads reach end of life and deorbit over time. A model increasing the in-orbit rate by 500 payloads a year (i.e., a linear growth rate versus exponential) is a fair estimate of the likely payload deployment rate for overall operational payload growth based on the last ten years of launch and end-of-life/decay data. Deployment of the smaller constellations will be more linear, while larger constellations will exhibit a more exponential growth for some period due to their large size and established production infrastructures. The SLP handles these large constellations outside of the 500 payloads/year growth rate. While forecasting future deployments is fraught with difficulty, merging of the extrapolated historical growth and open-source reporting of the largest announced planned constellations (greater than 1,000 satellites) leads to an overall population estimate. The uncertainty of the population grows over time as the confidence weakens for future projections (±14% by 2030 and ±34% by 2035). These uncertainty bounds are shown by dashed lines on Figure 7.

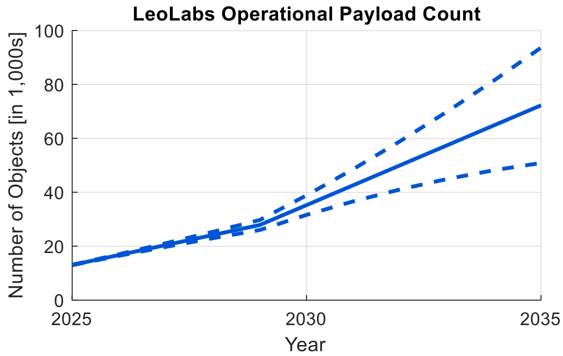

Figure 7. Estimated number of operational payloads over time per SLP

Mapping 2034 Projections in Inclination and Altitude

In 2024 Oltrogge et. al.'s work "Contrasting the Inflection Points and Efforts in Space Traffic Coordination and Management" [1] incorporated data collated based on ITU and FCC filings, as well as other public reporting, on large constellations which have been proposed for fielding by 2034. It is important to note that not all of these large constellations are likely to manifest; at the time Oltrogge et al observed that the success rate of fielding proposed constellations was around 13%. Often data from public disclosures is not comprehensive and data gaps need to be filled with estimates to produce an adequate dataset for research purposes. This data is for illustrative purposes only, since there is uncertainty regarding whether the proposed constellations will actually manifest and some data is estimated. For the purposes of this paper, sketching out the interaction between servicing architectures and potential client populations, the dataset is used to generate an estimate of a potential dispersion of large constellation satellites in altitude, inclination, and RAAN. While the exact future developments are unknown, this data collated from public sources illustrates patterns in potential usage of various altitudes and inclinations for emerging LEO applications.

The dataset from Oltrogge et. al. is plotted here in 3D space, with Figure 8 showing the altitude, inclination, and RAAN of each satellite plane ("alt-inc-raan"). The number of satellites in the plane corresponds to the size and color of the dots. The data is plotted like this to illustrate the "reachability" of populations of satellites by a single servicing mission. A servicing mission with a large DV budget can raise and lower its orbit by a substantial amount and can leverage differential precession to drift through a slice of RAAN, but inclination change is very limited due to the exorbitant amount of DV required (and time, when using EP). Therefore, an example “reachability envelope” is plotted in grey along with the satellite population, since several clients within such an envelope could likely be serviced by a single mission, but any clients outside of this would take an excessive amount of DV and/or time to reach making it more efficient to use a separate mission.

One fortunate observation from this map is that satellites often seem to cluster at certain inclinations, allowing one servicing mission to provide service to satellites from multiple constellations if the inclinations of the two constellations are matched or nearly matched. This makes sense, as a given mission picks its inclination based on various market and mission needs, and those tend to be similar for similar types of missions regardless of the operator.

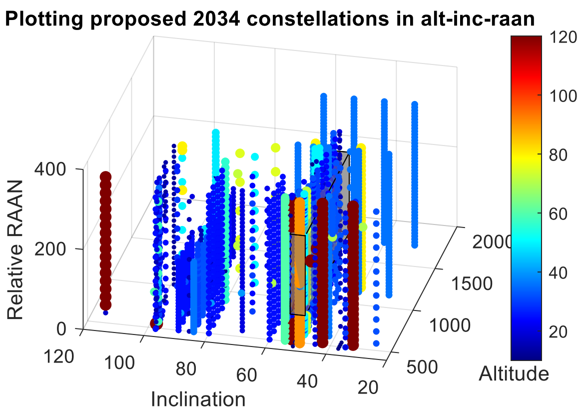

Figure 8. When proposed constellations are plotted in alt-inc-raan space clusters at certain inclinations are observable.

To illustrate the distribution in altitude and inclination more clearly, Figure 9 and Figure 10 show histograms of the dataset in altitude and inclination. This shows the low-50s are a very popular inclination, with concentrations also appearing in the 40s, 80s, and just below 100 deg. This grouping in inclination is key to the serviceability of populations from multiple constellations. For the purposes of this study, this dataset is considered to show an approximation of potential groupings in inclination for future traffic. While many more constellations are proposed than actually reach orbit, this dataset collects the constellations’ parameters that operators have expressed serious interest in, and these trends are worth examining even if the exact manifestation of future constellations is different from this particular set of license proposals.

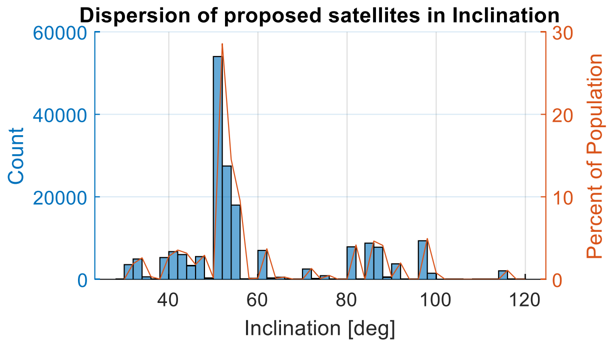

Figure 9. Histogram and normalized data showing dispersion of proposed satellites in inclination

For the dispersion in altitude there are also distinct groupings, though there are more groupings spread throughout LEO. This is manageable when considering the serviceability of populations, since changing altitude is much more reasonable than changing inclination in terms of DV and mission time. Also, servicing multiple constellations dispersed in altitude may even be a benefit to a servicing mission that is servicing planes at multiple RAANs, as a difference in altitude is necessary to produce a differential rate of RAAN drift and change RAAN relative to client satellites. Like inclination, this estimated dispersion in altitude is coupled with the total population predicted by the SLP model to investigate potential serviceable populations for the purposes of this study, but the study results are much less sensitive to dispersion in altitude than to dispersion in inclination.

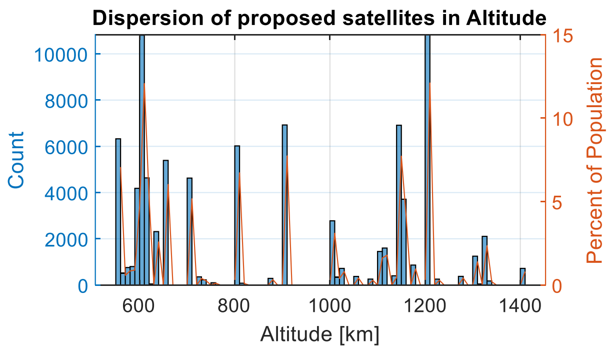

Figure 10. Histogram and normalized data showing dispersion of proposed constellations in altitude

A final note about altitude: satellites below about 600 km are not considered for this assisted disposal study, since they wash out quickly due to drag and are unlikely to need assisted disposal services in order to avoid accumulating derelict traffic. This study focuses on satellite populations above 600 km, where any non-functional satellites persist for much longer and would accumulate concerning populations of derelict traffic, potentially colliding and increasing the LNT risks to active satellites.

2.2.2 Failure Rates of LEO Population

LNT debris failures

LeoRisk determines the statistical probability of collision (PC) between any existing or hypothetical object or constellation against the current population of trackable and lethal nontrackable (LNT) objects. It uses the LeoLabs public catalog to determine the PC from the trackable population.

For the LNT population, LeoRisk uses the European Space Agency's Meteoroid And Space Debris Terrestrial Environment Reference (MASTER). Characteristics of the constellation (e.g., altitude, inclination, satellite size) and the evolving collision hazard can be modified to examine operational tradeoffs.

It determines the collision hazard for a space system now and over the course of its proposed mission lifetime in one-year increments. The growth rate of the LNT population (from 1 cm to 10 cm) is scaled based upon the estimated catalogued fragment growth in each year in 10 km increments from 400 km - 2000 km. This fragment growth is based upon the primary growth of new events and decayed fragments between July 2014 - July 2024 (~50/year) and the probability of collision by large intact derelicts in known clusters across LEO. This model is described in more detail in [10].

In addition, this paper simulates a collision scenario between a rocket body and payload at 950 km in 2030 and the lingering effects such a collision could have on the LEO LNT population from 2030 – 2035 (Figure 11).

This study considers the population down to 1 cm characteristic length to be lethal. Spacecraft can be resilient to small impactors, and the 1 cm population in MASTER has correlated well to reported anomalous debris events in the past [20].

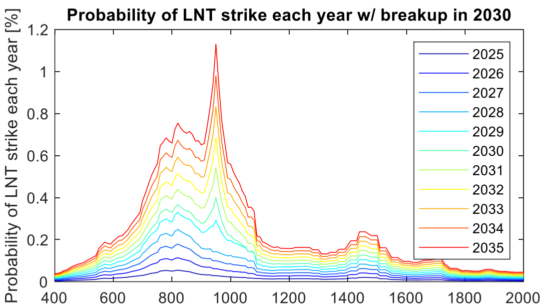

Figure 11. LeoRisk output for 1 m^2 satellite, showing probability of strike for each year using fragment growth per SLP

Since most missions fly for more than a year, this study uses the annual probability of strike returned by LeoRisk and extrapolates it to a 5-yr mission flown in the same environment (i.e, same baseline risk). For this study, two rates of LNT failures for 5 year missions are used. The current 2025 baseline LeoRisk estimated probability of strike is used as a lower limit, considering the probability of strike on a 5-year mission given this annual rate. To assess potential strike rates for future populations, the 2030 LeoRisk projection with one major breakup is applied over a 5-year mission as the upper bound on nearer-term LNT failure rates (Figure 12).

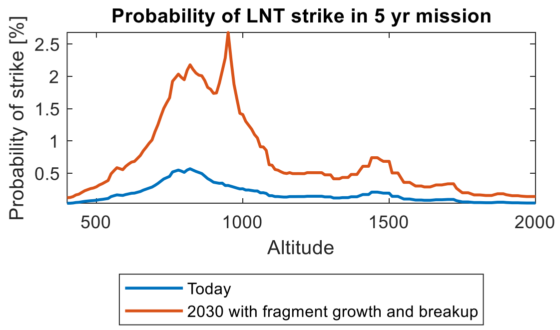

Figure 12. Taking the annual probability of strike as a baseline the total probability of strike in a 5-year mission is shown for the current LNT population and modelled 2030 LNT population

Non debris causes

The failure rates of spacecraft from non-debris causes are evolving over time, so the model parametrically trades a few values to assess the possibilities. The failure rate from operational constellations populating LEO with new non-operational PLs in the population model is largely driven by a few large enterprises with sub-1% failure rates over the last few years. The model in Figure 13 shows these values in the blue lines, which has resulted in limited growth from the first couple of large constellations. Note that this low growth rate is influenced by the rapid rate at which non-functional satellites deorbit from low altitudes where the largest constellation so far is located and by the operator's decision to actively de-orbit old satellites.

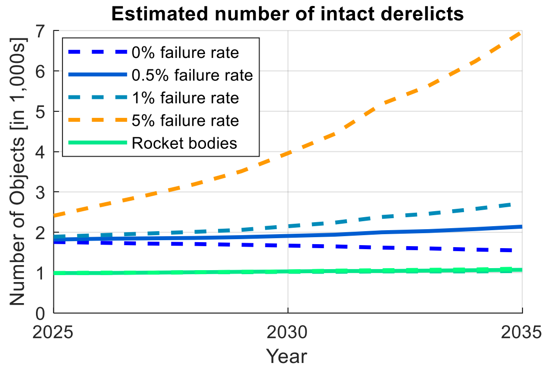

Figure 13. SLP model for non-operational payloads under various assumptions.

However, these low failure rates may prove to be overly optimistic. If future constellations have higher failure

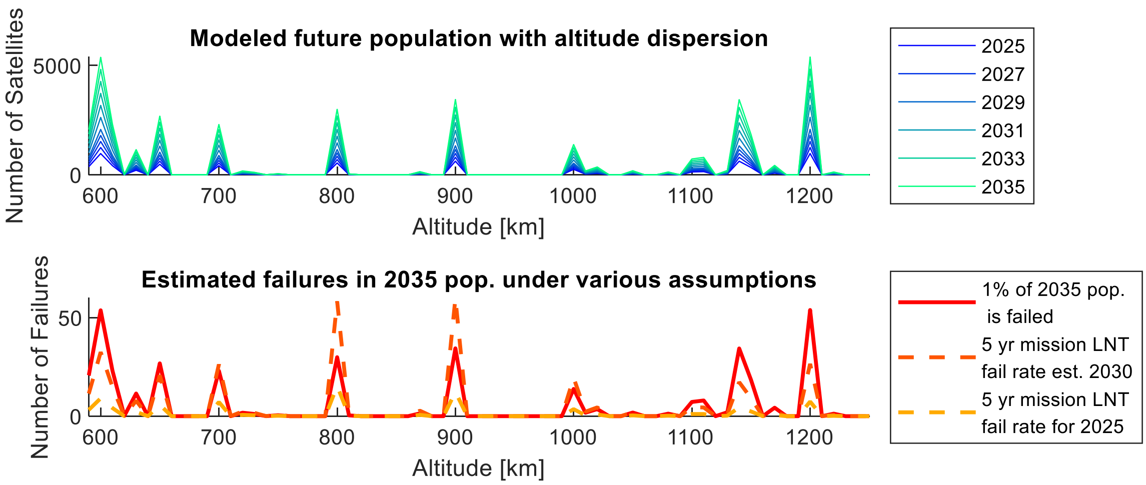

Figure 14. Leveraging future population estimations and failure rates to assess potential populations in need of servicing

rates (i.e, 3-5%) then the population model will exhibit significantly more growth. There have been concerning trends in the past year with some countries exhibiting high failure rates on initial launches for large constellations, coupled with several instances of launch vehicle fragmentation events which have demonstrated a slowness to address issues and contributed substantially to the debris population.

Because of these concerns, the orange line representing a 5% failure rate is added to Figure 13 to illustrate the trend if additional large constellations are not able to match the sub-1% failure rates of the early large constellations. This may prove to be the case, since OneWeb's current constellation only numbers in the 100s, and Starlink flies at a low altitude where satellites de-orbit fairly quickly at end of life, limiting the contribution either constellation makes to the population of non-operational satellites. Also, both launch to a low altitude and then raise to their operational orbit [21, 22], a technique which mitigates the effect of early failures in the spacecraft lifecycle and ensures only functional spacecraft are at operational altitudes. If newer operators don't follow this norm and have a significant failure rate, the population of derelict traffic would accumulate quickly. Due to this complexity and uncertainty, this study parametrically trades a few variables to obtain the non-operational population to consider for servicing, as discussed further in Section 2.3.

2.3 Coupling Service Architectures to Clients

After sketching out potential servicing mission architectures and mapping projected populations and their potential failure rates, the final step is to assess the interactions of these to map the population-in-need-of-service to the potential capabilities of mission architectures. Given the large uncertainties on failure rates which would generate the population of satellites in need of assisted disposal services, a variety of assumptions are applied to assess snapshots of the large parametric tradespace and sketch out mission concepts to address the needs of the population. There are myriad additional factors which influence the usage of servicing architectures, these are discussed in more detail in Section 2.3.2.

To begin, the total operational population count from the SLP model is coupled with the altitude distribution from the 2034 proposed constellation dataset (Figure 14). This provides an estimation of population growth over time at various altitudes. While this shows the total population growing consistently, in reality these constellations will be built out at various rates and times, but this is certainly manageable for servicing since having tighter clusters in altitude and inclination would tend to improve rather than degrade the reachability of the serviceable population.

The next step is to assess the expected failures of this population to investigate the population-in-need-of-service, results are shown in the lower chart of Figure 14.

There are several factors in play here, so three snapshots are chosen to illustrate the concept. First, one percent of the total 2035 population is assumed to have failed. This is slightly higher than the on-station failure rates of established large constellations to date, based on radar observations of satellite activities, but new constellations are showing higher failure rates. The operational choices of the constellation also have an impact: when constellations are launched to high-altitude deployments any satellite failure remains in orbit, as seen with recent large constellation launches by some countries. However, other operators have established a practice of launching low and raising orbit, which results in early failures washing out quickly and ensures that only satellites which are initially operational remain on orbit.

The second two snapshots pertain to the failure rate from LNT debris populations. Recall that tracked derelicts are a manageable risk for active satellites, as they can maneuver to avoid close conjunctions, but the population of lethal non-trackable debris presents a risk to operational satellites that is difficult to mitigate, and this population is expected to grow over time due to a variety of factors as described in [10]. The first snapshot uses the current 2025 baseline for LNT populations, which leverages the MASTER modelled flux at 1 cm as the LNT population, which is concordant with on-orbit observations [20]. This baseline for annual rate of strikes is used to assess the probability of lethal strikes over a 5-yr satellite mission, representing a “best-case scenario” with no growth to the current modelled population. To assess the potential impacts of near-term LNT growth, the second LNT baseline is the 2030 population, which has annual growth commensurate with expected growth in the fragment population plus the addition of one major breakup. This represents a potential future population that is larger than the current LNT population, as the population is expected to grow over time. This failure rate is also assessed for a 5-year mission life.

Using the altitude dispersion from proposed constellations, the total population from the SLP model, and the three scenarios to assess snapshots of projected failure rates, Figure 14 shows the resultant estimated population of satellites in need of servicing for the 2035 population of operational satellites.

Finally, recalling the strong dependence on inclination to the reachability of satellites by a servicing mission, the populations in need of service from Figure 14 are now plotted in a multi-dimensional histogram in Figure 15 to assess their dispersion in altitude and inclination. This shows the 1% failure rate applied to the 2035 estimated population. Reassuringly, the population is nicely grouped in inclination, with a significant serviceable population in the low-50s and the mid-80s.

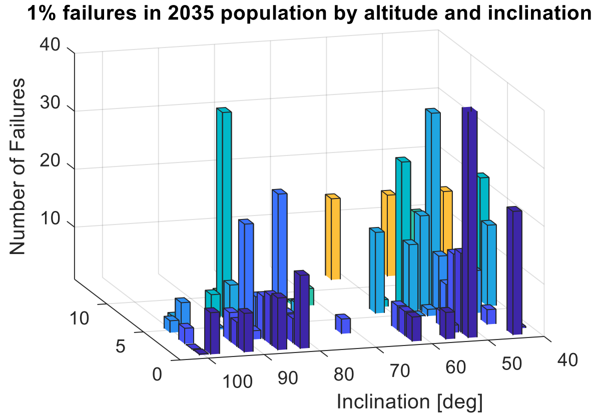

Figure 15. Estimated satellites in need of service vs. dispersion in altitude and inclination

2.3.1 Design Reference Mission

To create a design reference mission, a random selection of client satellites is developed from the proposed population. First, the proposed population is winnowed down (removing random satellites) until the total number of satellites is comparable to the SLP population prediction for 2035. Then a 1% failure rate is applied to these satellites, such that a random 1% of this reduced population is considered non-operational and in need of servicing. As shown in Figure 16 this produces a potential client population with altitude, inclination, and RAAN specified from which to select clients for a design reference mission.

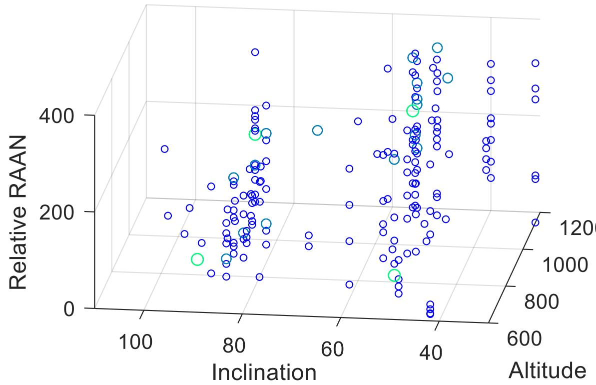

Figure 16. Randomizing 1% of 2035 population as "failed" satellites, to assess potential client populations

Nine client satellites which are clustered in altitude, inclination, and RAAN are selected for the design reference mission. Then the DV calculation approximations described in Section 2.1.2 are used to generate the flight path, approximate DV required, and mission time (Figure 17).

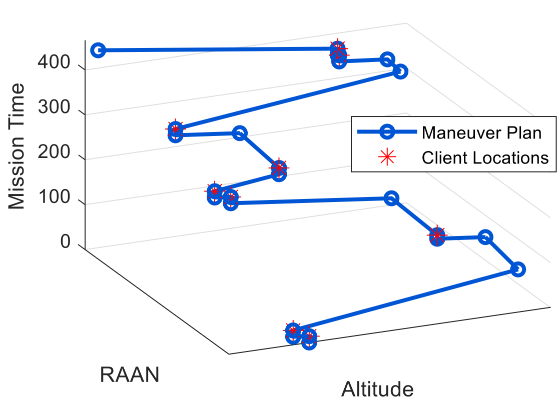

Figure 17. Design reference mission flight path in altitude and RAAN, with client locations

The RAAN drift episodes are included in the mission time, but it is assumed that RAAN drift does not occur during operations – this simplification assesses the DV applied, but a different client list would be selected as more optimal if the differential RAAN drift during each operation were taken into account.

This design reference mission takes about 15 months and is within the DV capabilities of both the multi-client servicer and the multi-plane servicer. The modelled usage of fuel for both propulsion systems is shown in Figure 18, along with the elapsed mission time as the design reference mission progresses through the series of maneuvers from client to client. This reference mission assumes that drag sails are placed on lower-altitude satellites and disposal pods are placed on higher-altitude satellites, but there is reserve fuel that could be used to de-orbit some clients with the servicer instead of placing deorbit devices on them. The final client is deorbited along with the servicer and could be a larger client which requires a controlled re-entry.

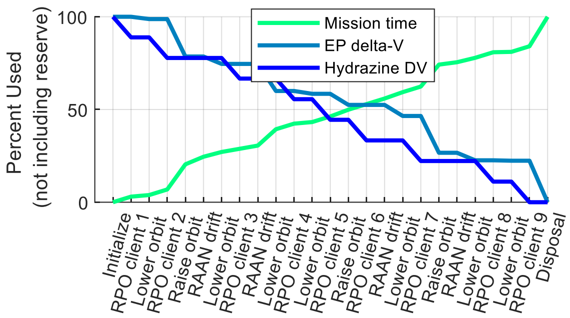

Figure 18. Design reference mission resource usage for each phase

2.3.2 Additional Factors

While these results show an encouraging picture of the serviceability of LEO constellations, it is time to discuss the elephant in the room: attaining availability and technical practicality of servicing would not necessarily imply that assisted disposal services will actually be used by clients. The actual usage rate would depend not just on the serviceable population of non-functional clients, but also on a myriad of other factors: economic, political, and legislative concerns all play a role.

For starters, the economic factors of obtaining servicing need to be favorable. Historically there have generally been no penalties for failing to comply with disposal requirements. In order to obtain a license operators must present a plan for complying with debris mitigation requirements, including disposal, but once satellites are on orbit there has historically been little to no downstream effects due to compliance with these plans (or lack thereof). This has seen changes in recent years. In 2023, the FCC fined Dish for failing to fully follow the disposal plan for their geosynchronous satellite [23]. While the amount of the fine was nominal, it set a precedent for the FCC's ability and willingness to enforce compliance in operations with the plans that licensing was contingent on.

More recently, the license for SpaceX's Gen 2 Starlink constellation includes a provision for routine assessment of constellation performance, and one of the parameters assessed the non-operational satellite lifetime on orbit against a benchmark. The benchmark is 100 object-years, which correlates to the constellation's contribution to derelict traffic on orbit. This ongoing assessment of constellation performance relative to a benchmark is an important development, along with the potential enforcement of negative consequences on the operator for exceedances. The specific benchmark to apply warrants continued consideration as described in the license, but the license observes that "An incremental approach based on a clear benchmark is appropriate" in the context of this development [22].

Together, these events illustrate a new willingness to impose costs on operators for non-compliance with responsible operational practices. This is favorable to servicing prospects, since historically the cost of non-compliance has been zero, making it very difficult to justify the expense of an assisted disposal mission. There is certainly a spaceflight safety cost associated with increases in derelict traffic, but it has previously been difficult to tie that cost to the actions of operators, making these FCC activities a critical component of developing the ability to fly large constellations while ensuring long-term spaceflight safety.

Another facet of the problem involves the relationship between the cost of a satellite, its reliability, and mission life. The reliability of a satellite is coupled to its cost – more expensive components and redundant systems drive up the cost and mass of the satellite. A constellation which employs cheaper satellites may be able to meet mission requirements but see higher rates of failures. If assisted disposal services are available to remove those failed satellites from orbit, the question is whether the cost of the disposal service balances out the cheaper cost of all the satellites across the constellation.

Similarly, satellites which are flown past the end of their planned mission life can be subject to age-related failures, but can generate additional value while operating for longer. Risking additional failures but gaining years of operational life across the constellation may likewise help to enable the employment of assisted disposal services with an improved economic picture. At the moment short-term LEO operations seem to be preferred, but this may change over time if use-cases require more capable (and expensive) satellites or additional cost for rapidly-refreshed systems emerges. For example, researchers have been assessing the impacts of satellite disposals on the atmosphere [24], which may eventually influence the use of rapidly deployed and deorbited satellites relative to more robust longer-lifetime satellites which require fewer disposals to enable the same mission.

Conducting active debris remediation on legacy debris objects could add a use-case for an assisted disposal mission which could improve the overall cost-per-use of the mission. The debris environment models have shown for years that a small amount of active debris remediation is necessary to stabilize the environment [25], but the high cost of these missions resulted in limited progress for many years. Recently, a few government organizations are proceeding toward demonstration missions [26, 27, 28], and these would need to become routine to stabilize debris growth over the long term. Leveraging developmental funding from the government to reduce burden of non-recurring engineering costs of active debris removal capabilities and then transitioning to commercial clients for routine operations, with legacy debris removal being one client among several for a given mission, would improve the economic factors and contribute to starting and then sustaining assisted disposal operations.

In summary, the economic and legislative elements of the problem play a key role in either facilitating or failing to facilitate assisted disposal architectures. While historically the business case for LEO servicing has been lackluster there are several emerging trends which may improve the adoption in this era of rapidly accelerating LEO populations. These considerations include the costs of derelict traffic, obtaining additional flexibility in satellite reliability and lifetime, and the close relationship between assisted disposal services and active debris remediation of older derelict objects. In order for these facets to materialize into an effective ecosystem of LEO constellations, servicing capabilities, and sufficiently low debris risks several actors will need to continue working on the various aspects of this ecosystem.

3 CONCLUSIONS

This paper develops concepts for assessing the interaction between future LEO populations, the satellites within those populations which may potentially need assisted disposal services, and potential mission architectures which could provide these services. The overall theme of this development is to sketch out a concept for assessing these, coupling technical analysis of maneuvers and reachable populations with probabilistic assumptions about failure rates and assessments of future population growth and dispersion in space. There are infinite ways to model and trade the myriad variables involved in this analysis, this study presents an early assessment using reasonable first-order assumptions to begin improving understanding of the relationship between specific servicing architectures and potential rates of use, which informs later understanding of potential cost per use.

Overall, the findings indicate that populations of LEO clients in need of service could be large enough to enable multi-client servicing missions in the relatively near term. While encouraging on a technical level, this finding is heavily caveated by the observation that a serviceable client population does not imply that clients will actually purchase services: the actual rate of service use is heavily dependent on economic, political, and legislative factors.

This means that developments at several levels among several actors will be required to facilitate future servicing architectures, it is not merely a technical challenge. It is important to not trivialize the technical challenges – experienced operators know that there is a very long road to get from illustrative concepts like the ones discussed in this paper to actually fielding operational technologies. However, the pace of those technical developments will be dependent on larger market factors, and it is the continued progress on developing these factors favourably that will ultimately determine the feasibility of routine operational assisted disposal services.

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5 REFERENCES

1. Oltrogge, D.L., Alfano, S., Berry, D. , Cooper, J., Vallado, D.A., and Kulu, E. (2024). Contrasting the Inflection Points and Efforts in Space Traffic Coordination and Management. *10th Annual Space Traffic Management Conference.* Austin, TX, 27-28 Feb 2024.
2. Kessler, D. J., & Cour-Palais, B. G. (1978). Collision Frequency of Artificial Satellites: The Creation of a Debris Belt. *Journal of Geophysical Research: Space Physics*, 83(A6), 2637-264.
3. McKnight, D, Arora. R, and Witner, R (2019). Intact Derelict Deposition Study. *First International Orbital Debris Conference.* Sugarland, TX, December 9-12 2019.
4. H. Krag et al (2017). A 1 cm space debris impact onto the Sentinel-1A solar array. *Acta Astronautica* 137 (Aug. 2017), pp. 434. doi: 10.1016/j.actaastro.2017.05.010.
5. Gruss, M (2016). DigitalGlobe says WorldView-2

operational after "debris causing event." *SpaceNews.* July 19 2016.
6. The Persistent Problem of Orbital Debris (2018). *Secure World Foundation.*
7. SDA Makes Commercial Disposal Services Study Awards Under STEC BAA (2024). *Space Development Agency Press Release.* September 26 2024.
8. Rainbow, J. MEV-2 servicer successfully docks to live Intelsat satellite (2021). *SpaceNews.* April 12, 2021.
9. Erwin, S. (2024). Northrop Grumman eyes 2026 launch of robot-armed satellite servicer. *SpaceNews.* November 14, 2024.
10. McKnight, D., Dale, E., and Kunstadter, K. (2024). Modelling Short-term Space Object Population Growth in LEO. *75th International Astronautical Congress (IAC)*, Milan, Italy, 14-18 October 2024.
11. Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (2010). *United Nations Office for Outer Space Affairs.* United Nations, Vienna, 2010.
12. U.S. Government. Orbital Debris Mitigation Standard Practices (2019). *orbitaldebris.jsc.nasa.gov.* November 2019 update.
13. Best Practices for the Sustainability of Space Operations (2024). *Space Safety Coalition.* SpaceSafety.org.
14. G.A. Henning, M.E. Sorge, D.G. Bologna, L. Wahleithner, J.C. Maldonado (2024). Correlating LEO sustainability to targeted debris mitigation methods using simple metrics. *75th International Astronautical Congress*, Milan, Italy, October 2024.
15. Erwin, S (2024). Starlink set to hit $11.8 billion revenue in 2025, boosted by military contracts. *SpaceNews.* December 16, 2024.
16. Maclay, T., Goff, J., Sheehan, J., Han, E (2020). The development of commercially viable ADR services: Introduction of a small-satellite grappling interface. *Journal of Space Safety Engineering*, Volume 7, Issue 3, 2020, Pages 364-368.
17. Smeltzer, S., and Wagner, N. (2023) ADR Mission Analysis Utilizing Nodal Precession. *Accelerating Space Scommerce, Exploration, and New Discovering (ASCEND) Conference.* October 23-25, 2023, Las Vegas, NV.
18. Erwin, S. (2024). Northrop Grumman's orbital refueling port selected for U.S. military satellites. *SpaceNews.* January 29, 2024.
19. Schaub, H and Junkins, J (2014). Analytical Mechanics of Space Systems, third edition. *AIAA Education Series.* ISBN 978-1-62410-240-0.
20. McKnight, D., Braun, V., Dale, E., Kunstadter, C., (2023). Rapid Collision Risk Assessment for Constellations, *International Orbital Debris Conference*, 4-7 December 2023, Sugar Land, TX, USA.
21. Henry, C. (2020). Soyuz launches 34 OneWeb satellites. *SpaceNews.* March 21 2020.
22. Request for Orbital Deployment and Operating Authority for the SpaceX Gen2 NGSO Satellite System (2022). *Federal Communications Commission.* FCC 22-91.
23. FCC Takes First Space Debris Enforcement Action (2023). *Federal Communications Commission.* DOC-397412A1. October 2, 2023.
24. Ferreira, J., Huang, Z., Nomura, K., Wang, J. Potential Ozone Depletion From Satellite Demise During Atmospheric Reentry in the Era of Mega-Constellations (2024). *Geophysical Research Letters.* June 11 2024..
25. Liou, J.-C (2011). Active Debris Removal – A Grand Engineering Challenge for the Twenty-First Century. *21st AAS/AIAA Space Flight Mechanics Meeting*. New Orleans, LA. February 13-17, 2011.
26. Rainbow, J (2025). Astroscale and ClearSpace reach development milestone for dual-satellite deorbit mission. *SpaceNews*. February 11, 2025.
27. Werner, D (2024). Major changes approved for ClearSpace-1 mission. *SpaceNews*. April 24, 2024.
28. Foust, J. (2024). Astroscale finalizes contract for Japanese debris removal mission. *SpaceNews*. August 21, 2024.