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# Operational Flexibility and Asset Retasking Enabled by In-Space Refueling

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## Abstract

Satellite mission lifetimes are often constrained by the amount of fuel carried by the satellite at launch. The amount of fuel needed for a mission is typically carefully calculated during mission planning to enable completion of planned operations for a nominal lifetime. This approach means that using fuel at a higher rate than initially planned to retask an asset or recover from off-nominal scenarios directly reduces mission lifetime; in practice this results in retasking or pursuing new operational opportunities being costly and rarely worthwhile for commercial and government operators. In-space refueling has the potential to remove this barrier and give spacecraft operators the opportunity to maneuver without regret to retask assets and engage in unplanned operations.

This paper presents several case studies of opportunities for retasking spacecraft and/or changing their operational mission profile. The case studies considered include relocation of GEO communications satellites between slots, reconfiguration of a LEO observation or communication constellation to provide additional coverage over an area of emergent interest, and relocation of satellite servicing vehicles between operational orbit regimes. For each case study, the feasibility with and without refueling is assessed and the technical and financial gains offered by refueling are quantified. The paper also presents an overview of the refueling technologies that Orbit Fab is developing to help enable refueling missions which will expand the operational capabilities and retasking options for satellite operators.

**Keywords:** Retasking, Relocation, Revisit, Refueling, Dynamic Space Operations

## Acronyms/Abbreviations

| | |
|---|---|
| ADR | Active Debris Removal |
| GRIP | Grappling and Resupply Interface for Products |
| ISAM | In-Space Servicing Assembly and Manufacturing |
| OTV | Orbital Transfer Vehicle |
| RAFTI | Rapidly Attachable Fluid Transfer Interface |
| UMPIRE | Universal Mission Planner to Investigate Refueling Effectiveness |
| VLEO | Very Low Earth Orbit |

## 1. Introduction

### *1.1 Orbit Fab Overview*

In-space refueling is changing the paradigm in the space industry by removing the constraints placed on missions by the limited amounts of fuel they can carry at launch. Orbit Fab is building the in-space propellant supply chain that will enable future missions to pursue entirely new options during operations. Orbit Fab has developed key enabling technologies that make in-space refueling possible. Two of these are the Rapidly Attachable Fluid Transfer Interface (RAFTI) and the Grappling and Resupply Interface for Products (GRIP). Orbit Fab will use these two technologies on its fuel shuttles and fuel depots to deliver refueling services to spacecraft. Fuel shuttles are designed to deliver to a customer spacecraft whereas the fuel depot is intended to store deliverable fuel and pressurant [1]. With vehicle mass at a premium on spacecraft the RAFTI service valve doubles as a ground fill and drain valve, expanding its capabilities [2] [3].

### *1.2 General Benefits of Refueling*

In launching spacecraft to orbit the mass budget is a driving requirement to achieve mission success. In traditional spacecraft that require pressurant and fuel these consume a large portion of the mass budget that otherwise consists of hardware that could generate value with the collection of data. Were the spacecraft not to carry as much or any pressurant and fuel at launch, the now unused mass budget could be allocated to hardware that generates more data and hence more value.

With hazardous fuels, like hydrazine, ground fueling operations are dangerous to human life and require special training and infrastructure. These factors drive costs up for traditional spacecraft. A spacecraft equipped with

RAFTI could postpone initial fueling until after it is in orbit, thus removing the human risk. This passes the training and infrastructure requirements from the customer onto Orbit Fab, decreasing their capital expenses. By launching the satellite with an empty fuel tank, one can now increase payload mass delivered and eliminate ground fueling costs.

Expanding a spacecraft or asset's capabilities may not be a priority of some missions but a mission extension may pay off greatly. Given the orbit decay of objects in LEO, mission designers must either accept the lifespan dictated by the decay rate or plan for station keeping. In either case, refueling a LEO spacecraft can stave off the natural deorbit date and make a replacement unnecessary. While GEO satellites do not deal with atmospheric drag decaying their orbit, perturbations from solar radiation pressure and 3rd bodies push the satellite out of its licensed station keeping box. If they are unable to maintain their orbital slot, they must vacate to a graveyard orbit. Refueling can extend the life of these assets that have a high initial cost to get to GEO. The business case for a spacecraft that is refuellable does not see the bounds that an expendable spacecraft has with its finite lifespan. Finally, lunar and interplanetary missions have in the past required heavy government funding and are designed around answer priority science questions from the decadal surveys. Refueling can decrease the capital cost of lunar and interplanetary missions to make them viable for commercial motivations.

## 2. UMPIRE and Previous Work

Rapid mission planning and conops optimization for ISAM and other missions requiring frequent orbit changes requires analytical models for mission planning that can be executed quickly, enabling fast iteration on mission plans that require many maneuvers executed over the span of years of operations. To address this need, Orbit Fab has developed an in-house mission architecture analysis/planning platform, the Universal Mission Planner to Investigate Refueling Effectiveness (UMPIRE). UMPIRE is currently used to architect optimal refueling logistics solutions to meet customer demand cases and develop mission plans for delivering fuel to customer spacecraft at the lowest cost and impact to mission operations. The UMPIRE software allows users to assess many different conops alternatives for individual spacecraft and overall mission architectures.

As the industry moves to a new paradigm of dynamic space operations and in-space services become available through refueling and other ISAM missions, the trade space of what can be accomplished with a mission is greatly expanded both in the pre-mission planning and operations phases. Because of this, there is an increasing need for analysis tools that can optimize architectures with economic and capability trades together. However, running analyses of this complexity can take months to configure and run with current commercial-off-the-shelf software and the fidelity could either be far higher or far lower than what a commercial customer needs. With more highly variable emerging conops across new market segments, legacy tools have proven a poor fit for optimizing on-orbit mobility-based architectures such as those benefiting from refueling and ISAM. UMPIRE was created to fill these gaps.

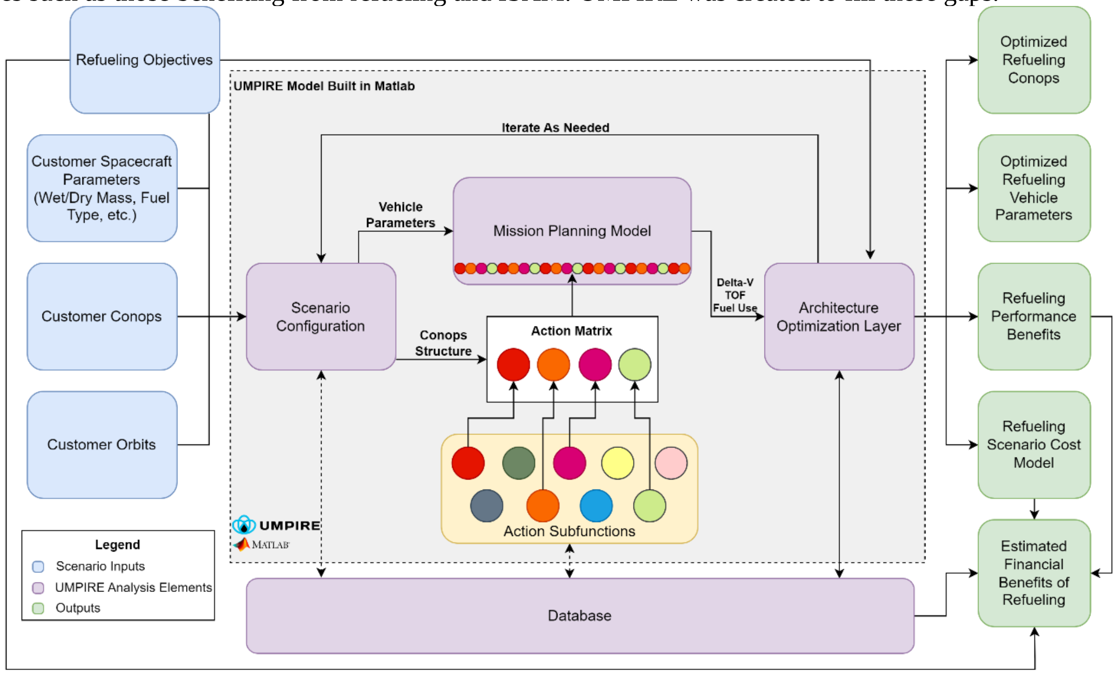

Fig. 1. UMPIRE Block Diagram

Fig. 1 provides a high-level overview of the structure of the UMPIRE software. UMPIRE works by allowing the user to easily script conops in the form of an 'Action Matrix' (which is a list of on-orbit actions/maneuvers), where each action type calls a specific sub-function calculating fuel, ΔV, and time. These fuel and time values are summed across the entire Action Matrix as UMPIRE works backwards to accurately account for future fuel mass needs. These case outputs can be fitted to cost functions, allowing multiple scenarios to be compared for several variables. UMPIRE is developed using analytical astrodynamics solutions wherever possible rather than propagation methods to ensure a quick runtime, further enabling comparison and optimization across a wide variety of mission alternatives. With this structure, UMPIRE allows tremendous flexibility and configurability to address trade studies of variable complexity and serves as an extremely valuable tool for assessing the benefits and viability of refueling for various mission scenarios.

## 3. Case Studies Examined

This paper highlights some of the capabilities of UMPIRE by showing results of UMPIRE analysis of three promising use cases for in-space refueling. Across several different orbital regimes and markets, operational flexibility and retasking can unlock large value propositions. However, as discussed above the ability of these assets to access the full extent of that value proposition by taking advantage of maneuvering in ways that were not anticipated at the spacecraft design stage is greatly limited by their on-board fuel. Refueling can change these paradigms for the better, with the magnitude of this benefit relying heavily on the orbital domain and use case of this satellite. Below, the potential of several of these cases are examined at a high level to display the implications of refueling enabled flexibility. First, Section 3.1 examines the case of relocating GEO Communications satellites between different slots in the GEO belt to respond dynamically to demand and maximize revenue potential. Second, Section 3.2 considers the prospect of reconfiguring an Earth observation constellation to respond to an emerging disaster scenario at an inclination the constellation was not initially designed to focus on. Finally, Section 3.3 examines the case of relocating servicing vehicles between different planes and altitudes in LEO for ISAM use cases. For purposes of this paper, data for a debris removal mission will be used, but the same approach is extensible to any ISAM use case and similar benefits from the reuse/reduction in number of expensive servicing vehicles can be expected.

### *3.1 GEO Communication Satellites*

Geostationary orbit (GEO) represents a huge percentage of the yearly revenue of the space market. Over 80% of the satellites operational in GEO serve communication purposes [4], and the orbital slots that each of these satellites inhabit is a highly valued commodity. Spectrum allocation over different portions of the world can significantly drive the market potential of these satellites, but they face fierce competition from both ground telecommunications providers and other space satellites/providers both in LEO and GEO.

To stay competitive as new markets emerge, spectrum allocations change, and global demand distributions shift, these GEO satellites may be relocated from one GEO slot to another once or several times over the course of their lives. Relocations may also occur in cases where a company or agency has spectrum allocated at a particular longitudinal slot that they are required to bring-into-use in order to maintain the allocation. In these cases, a spacecraft may be relocated to hold the slot in advance of a future mission [5] [6]. As conventionally these satellites are non-refuellable, each time they relocate the maneuvers cut into their fuel margin for station-keeping, reducing the overall amount of station-keeping fuel they have and thus their overall operational lifetime, limiting revenue potential and profit. Additionally, there is a trade between speed of longitudinal relocation and fuel mass required.

GEO satellites are spread covering different longitudes of the Earth. Fig. 2 shows the longitudinal distribution of GEO spacecraft as of May 2022 [4]. A higher number of satellites around a given longitude suggests a more in-demand slot allocation. This distribution has not been constant over time and has evolved as global telecommunications systems and demand have shifted [7]. As this service demand evolves, satellites may need to relocate up to 180° in front of or behind their current longitude. Depending on the magnitude of this relocation in degrees, more ΔV and time may be required. A typical GEO station-keeping budget requires roughly 60 meters per second per year of ΔV. The ΔV expended to relocate can then be traded against the fuel lifetime lost to estimate the impact on the satellite's mission. Fig. 3 explores this relationship between relocation and GEO station-keeping fuel lifetime.

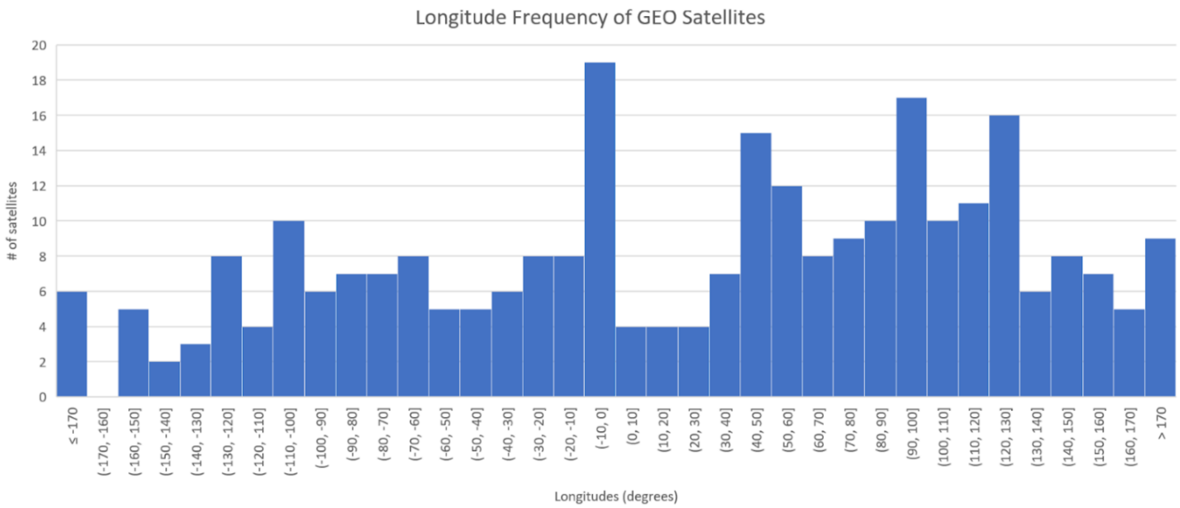

Fig. 2. Longitudinal distribution of GEO Satellites *[4]*

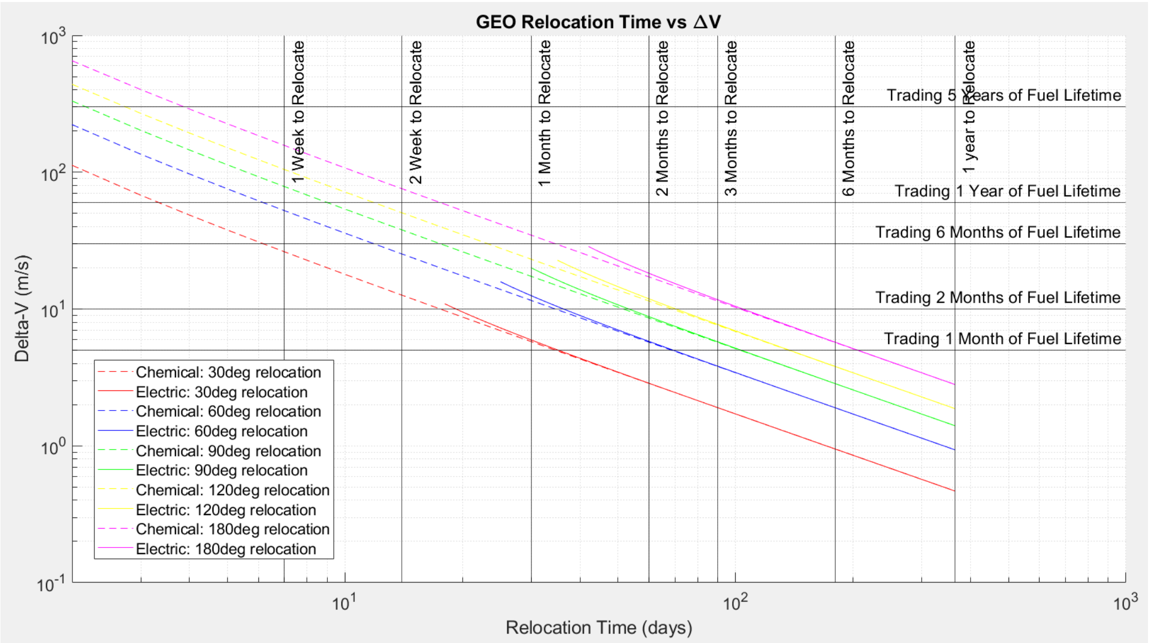

Fig. 3. Time vs. ΔV for variable degrees of relocation in GEO

Several valuable conclusions can be drawn from the data in Fig. 3. For instance, if one were to spend 2 weeks relocating 180° this would cost them roughly 1 year of fuel lifetime, but if the relocation time were doubled the reduction in fuel lifetime is only around 6 months. This trend continues as longer relocation times logarithmically reduce the traded fuel lifetime. Along these same degrees of relocation, if 6 months of transit time are spent to relocate, only 1 month of fuel lifetime is traded. Of note, electric propulsion being thrust-limited means that for short relocation times chemical propulsion is required. Fig. 3 was generated assuming the chemical propulsion had 100 N thrusters and the electric propulsion had 80 mN thrusters for a 3,000 kg satellite.

Where on this spectrum operators decide to plan their relocation maneuvers depends on a number of factors. In highly competitive GEO slots that require significantly faster relocations, operators may balance the time vs ΔV trade based on projected revenue potentials or service disruptions. The greater the need for speed or projected number of relocations, the more lucrative refueling becomes as an option for life extension of an asset compared to the cost of replacement.

Orbit Fab has completed an example case study for relocation scenarios. To run a simplified cost trade study for a single satellite, we assume the following over the course of this scenario:

- The first relocation occurs when the asset has 10 years of remaining fuel life.
- The satellite utilizes monopropellant hydrazine for station-keeping and phasing.
- The satellite's dry mass is 2,500kg.
- Each relocation is for 180° of longitude.
- The average price of fuel in space is $200,000/kg delivered to the satellite.
- The satellite generates on average $100 M/year in revenue (USD).

Two cases of the scenario were considered in the UMPIRE analysis. In Case 1 it is assumed that the satellite has a set lifetime that cannot be extended beyond the 10 years of remaining fuel due to avionics or licensing limitations, and that all refueling is to replace the fuel lost over the course of N relocations. In Case 2 it is assumed that the satellite can exceed the remaining 10-year lifetime with an additional 5 years of operation enabled by refueling to generate additional revenue over the course of the relocations.

Each case was analyzed with and without refueling in order to quantify the benefits offered by refueling in terms of the estimated revenue over the course of the lifetime of the spacecraft using various relocation approaches. Both cases begin with the estimated lifetime revenue of the spacecraft and then adjust based on additional costs for the given scenario. The non-refueling scenarios incorporate the lost revenue costs of transit time and lifetime reduction (due to fuel expenditure), while the refueling scenarios incorporate the lost revenue costs of transit time and the cost of refueling in space to maintain (Case 1) or exceed (Case 2) the initial remaining satellite lifetime. It is important to note that the output in this analysis is only an adjusted relative revenue comparison. The number does not reflect profit directly as operation costs and amortization of asset costs are not included. Additionally, added revenue above the baseline assumption offered by relocation to a different slot are not modelled as these will be highly scenario dependent for each operator. As such this serves as a useful agnostic adjusted revenue (as it only incorporates the cost of fuel), so these curves can be utilized against anyone's own cost curves to calculate their profits. Orbit Fab works with customers to incorporate more detailed revenue models for their cases as desired and needed to help close business models and mission plans around refueling.

Figs. 4-7 show the results of the GEO Relocation scenario produced by UMPIRE. Fig. 4 and Fig. 5 both show the effect of relocation transfer times on adjusted revenue with and without refueling depending on number of relocations. Without refueling, these curves follow a convex inverted U shape where very fast and very slow transit times both show significant reductions in adjusted revenue. Slow transit times reduce adjusted revenue by increasing the amount of time the asset is out of service while relocating, while the fast transit times reduce adjusted revenue because of the significant fuel expenditure. With refueling added to make up for this fuel expenditure, fast transfer times show very little adjusted revenue loss. In the case where refueling is also used for life extension, shown in Fig. 5, the benefit is even larger as the offset in fuel expenditures for fast transfers can be compounded with benefits from life extension.

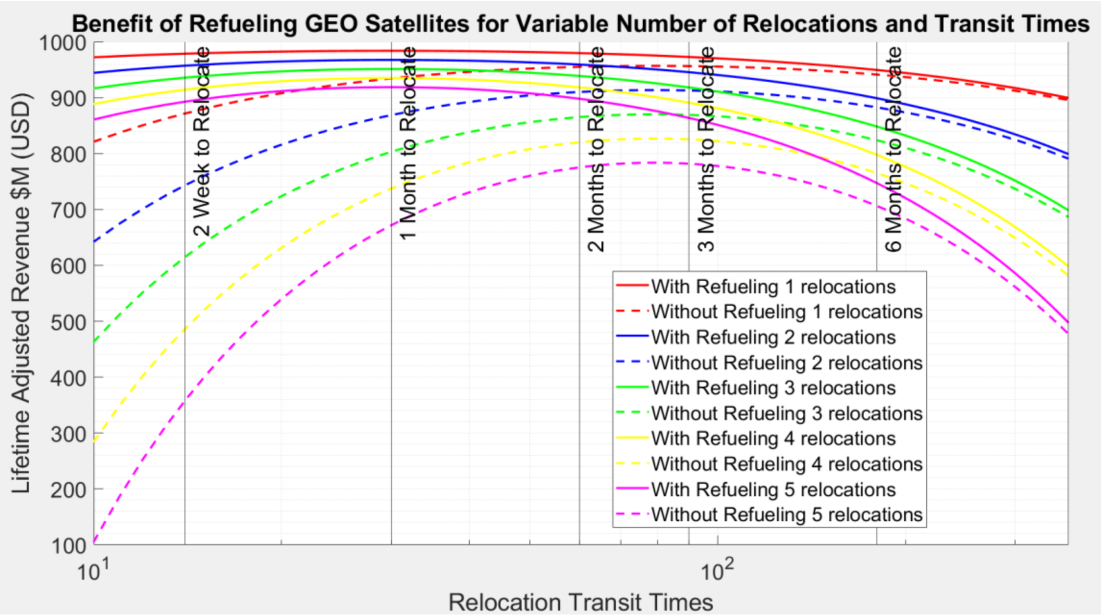

Fig. 4. Relocation transit times versus lifetime revenue for variable number of relocations, without life extension

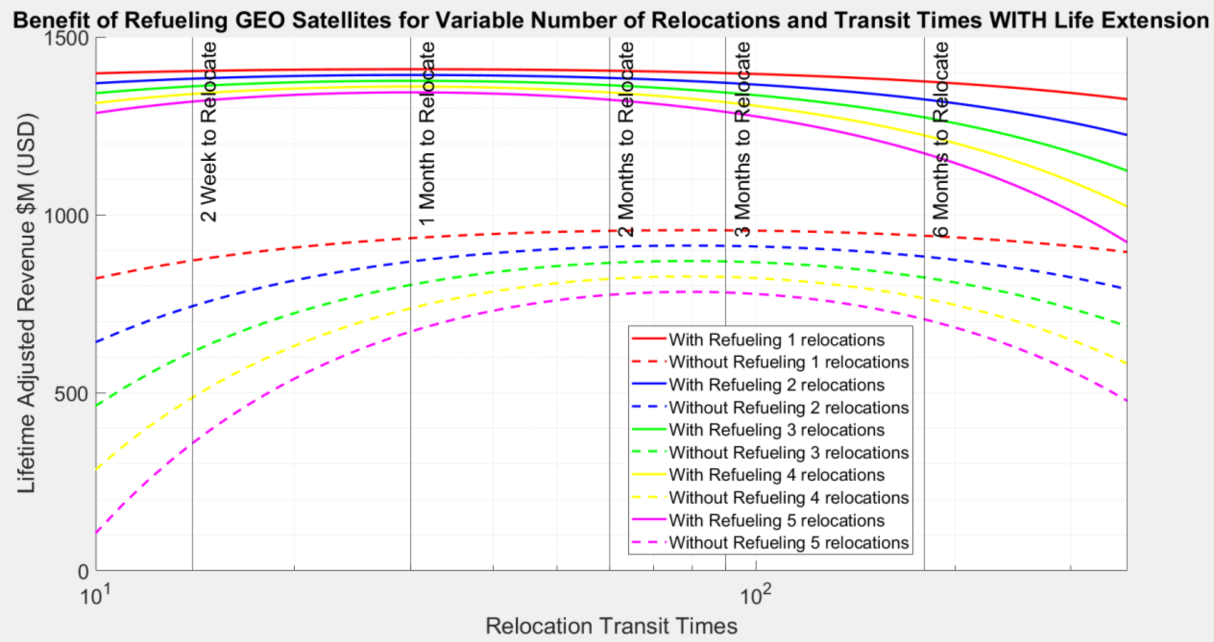

Fig. 5. Relocation transit times versus lifetime revenue for variable number of relocations, with life extension

Next, the maxima of each of the curves in Figs. 4 and 5 were identified as the optimum adjusted revenue transfer times for each scenario. This allowed a transit time optimized adjusted revenue comparison between the refueling and no refueling cases to be generated (Figs. 6 and 7), which demonstrates that revenue can be maximized for any number of relocations by using refueling, even after the costs of fuel in space are considered. The benefit of refueling increases significantly as the number of relocations increases, clearly showing that operators who need to perform numerous relocations over their mission life stand to benefit substantially from refueling in space. Again, it is important to note that Figs. 6 and 7 do not include potentially higher revenue generation rates of the new longitudinal slot compared to the prior slot as that parameter is heavily dependent on a particular operator's business model, and it is assumed a relocation will be pursued only if generally beneficial to the operator.

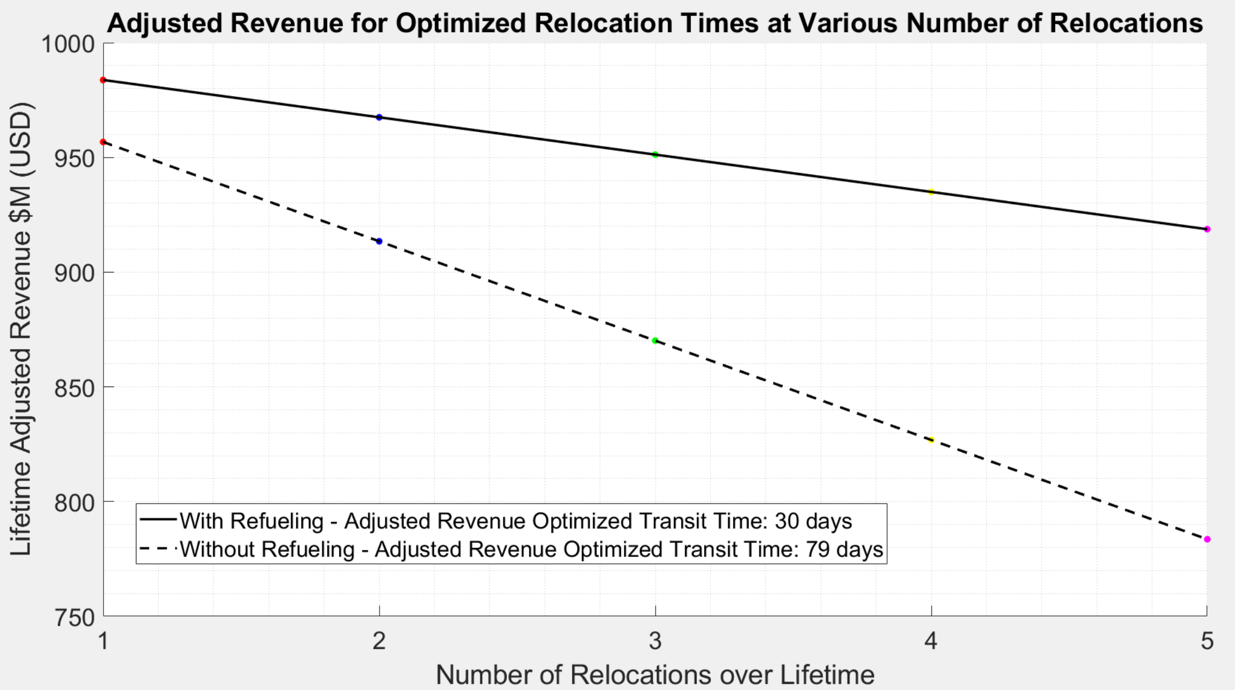

Fig. 6. Number of relocations versus lifetime revenue with and without refueling, without life extension

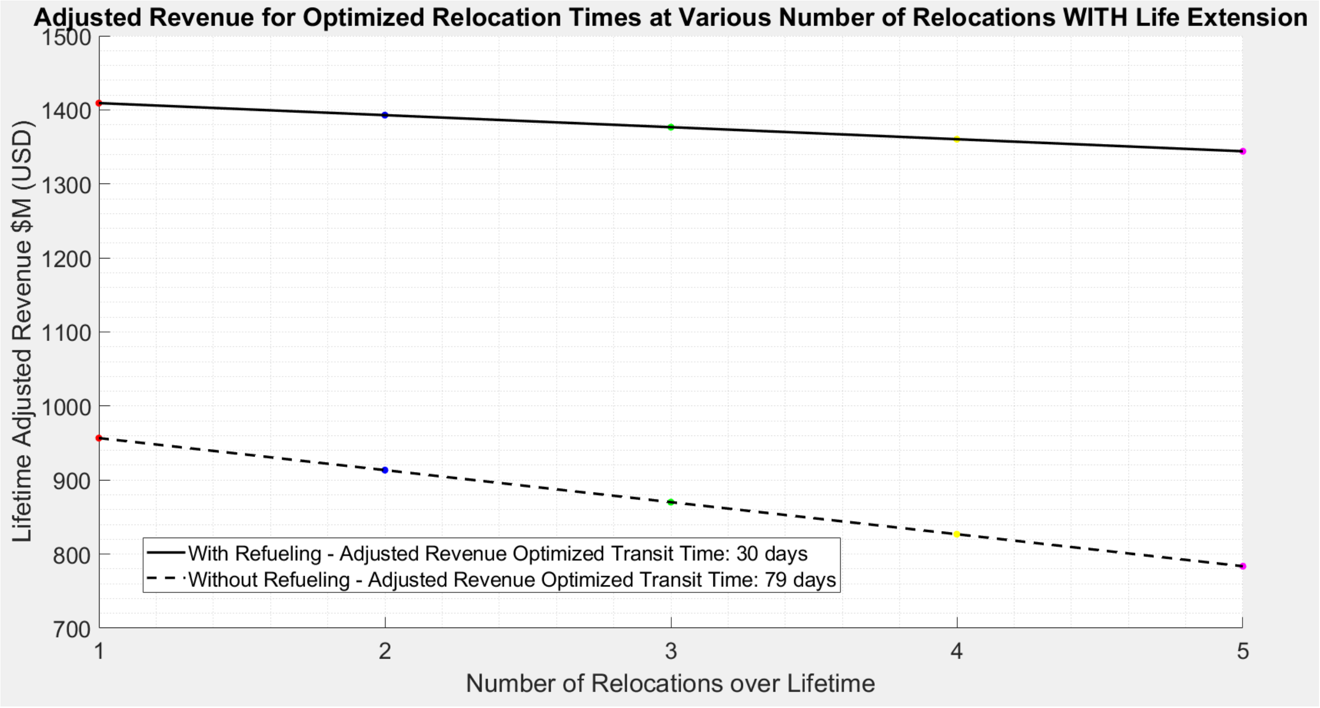

Fig. 7. Number of relocations versus lifetime revenue with and without refueling, with life extension

Overall, Figs. 4-7 strongly display the positive benefits of refueling, enabling faster relocations, more relocation flexibility, and life extension. Coupled together, these benefits can make for extremely competitive and flexible assets that can dynamically respond to changing markets and world events. This case was heavily simplified to be agnostic, but generally representative of the GEO market. When applied to a customer use case based on an actual specific mission plan and business model, this approach can be used to optimize a mission plan around a refueling solution that maximizes mission value. Significantly more detailed and diverse use cases can be run using UMPIRE and optimized to provide the greatest technical and economic benefit.

### *3.2 LEO Earth Observation or Communication Satellites*

Low Earth Orbit is an increasingly proliferated domain home to numerous Earth observation and communication constellations. When designing placement for Earth Observation constellations, the value proposition tends towards lower latitudes where the majority of Earth's population and usable land is. As more Earth Observation constellations emerge, they may tend towards choosing this to take advantage of rideshare opportunities to popular mid-inclination launch locations such as inclinations of 53° (around Starlink and near ISS). Potential issues with this approach arise when needs appear in higher latitudes than can be seen by these mid-latitude constellations. Relocation of assets is possible using refueling, but this requires a high enough value proposition to justify.

Natural disasters represent cases with huge potential losses, where any additional data prior, during, and after disasters can save multitudes of lives, prevent total infrastructure collapse, and help better target relief efforts. As such, the value proposition both from a utilitarian and monetary perspective can be huge for disasters of large magnitude. For example, Oddo and Bolten's study of earth observation for emergency response found tens of millions of dollars in savings for each minute improvement in the response time over emergency services and concluded that "Results indicate a potential significant economic benefit (i.e., millions of dollars) from applying near real-time Earth observations for improved flood disaster response and management." [8]

Many of the populated regions most prone to natural disasters exist at low latitudes in tropical climate zones or active volcanic and tectonic regions, but over the past decades northern latitudes have seen larger rates of population growth offering a greater potential risk than these areas may be prepared for judging by historical trends. Climate change worsens this, as rapidly changing weather patterns can bring unmitigated and unprojected harm to these unprepared regions. The exact impact of climate disruption is extremely difficult to project, but in response to these potential emerging situations larger value propositions at these higher latitudes may emerge over the course of a constellation's lifetime.

Of course climate change is not the only risk at these high latitudes. The Ring of Fire surrounding much of the Pacific Ocean has some of the most frequent and catastrophic tectonic activity in the world. The Ring of Fire stretches much beyond the mid latitudes to northern regions such as the Aleutian islands and Southern Alaska. As such this area is prone to devastating earthquakes and tsunamis which can cause massive death tolls [9]. In 1964, this tectonic activity caused the Great Alaskan Earthquake centered near Anchorage, Alaska. It was a 9.2 magnitude on the Richter scale with the earthquake and subsequent tsunami causing 139 deaths and $2.94B in damages (adjusted for inflation) [10], with impacts from the tsunami that could be measured as far south as Australia. Since then, Alaska has experienced a number of large magnitude earthquakes, with 8.0+ magnitude earthquakes occurring on average every 13 years, putting at risk the population that has nearly tripled since 1964 [9]. Depending on the epicenter and geographic orientation of tectonic activity along the northern edge of the ring of fire, the earthquakes and subsequent tsunamis could pose even greater total damages and loss of life than The Great Alaskan Earthquake. As such this represents a valuable case study for LEO constellation retasking.

A model of Earth observation asset retasking based on the Great Alaskan Earthquake scenario was built using UMPIRE to quantify the benefits of refueling for this case. A modest Walker Delta constellation of 16 satellites split across 4 planes at 53° inclination and 400 km altitude was assumed. The greater Anchorage region and semi-adjacent counties are assumed to the primary areas affected. An area in the Amazon is also selected as a reference area for the baseline imaging performance of the mid-inclination constellation. The constellation will be retasked to maximize observation performance of this region and the impact of doing so is quantified using UMPIRE. The initial performance of the ground constellation can be seen in Fig. 8.

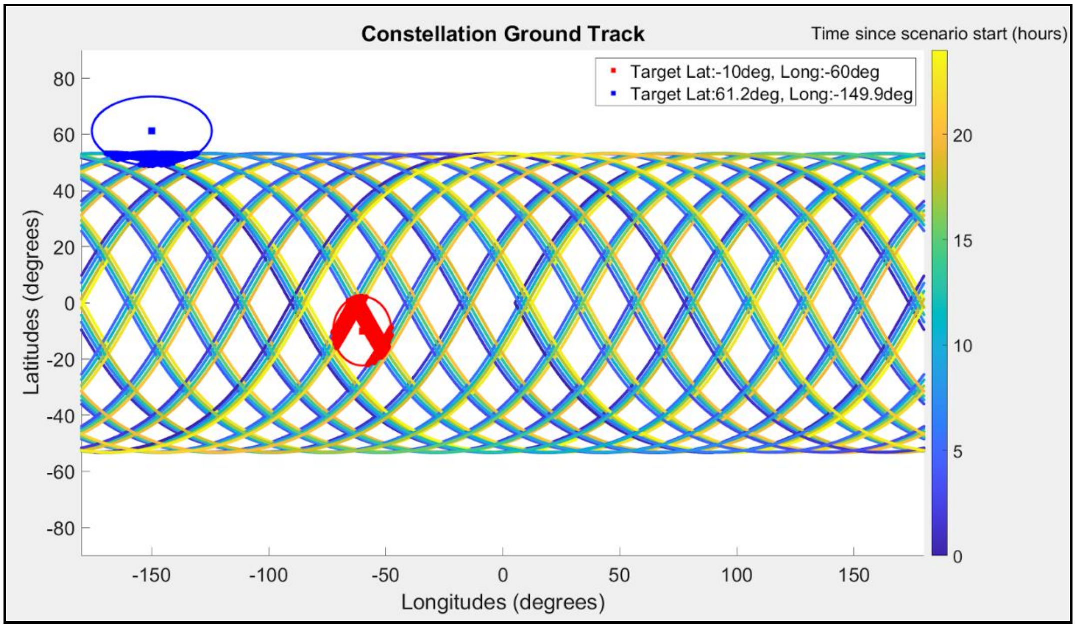

Fig. 8. Starting walker delta constellation ground track including targets

The sinusoidal lines represent the ground tracks of all the satellites in the constellation over a 24-hour period, color scaled to show the positions relative to time. The red square represents a ground target for observation in the Amazon rainforest whereas the red ellipse and dots within represent the rough range within which the constellation can observe the ground target. The blue square represents Anchorage, Alaska whereas the blue ellipse and dots within represent the rough range within which the constellation can observe Anchorage. Fig. 9 shows the pass distance relative to the ground targets within the 24-hour period. The red curves represent the pass distance relative to the Amazon target. The blue curves represent the pass distance relative to Anchorage.

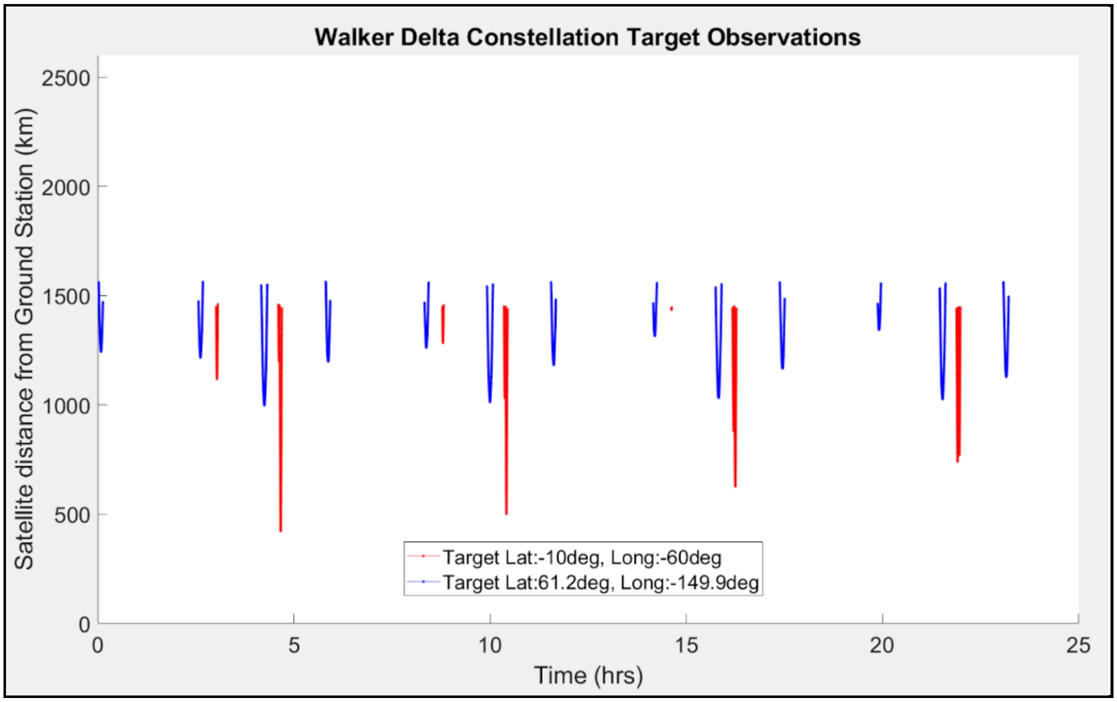

Fig. 9. Starting walker delta distance from passing satellite to ground targets

For emergency scenarios the coverage time and revisit rate are among the most important parameters in assessing the performance of the constellation. These directly impact the timeliness of data that can inform emergency response efforts. The average pass distance is of some significance as well as it affects the resolution of images produced, but this highly depends on the capabilities of the constellation initially. It is possible that resolution can be sufficient in some cases without changing the average pass distance. In order to determine the optimum way to reconfigure the constellation, the baseline performance of the constellation for imaging the Anchorage target area will be used as a reference. For the Anchorage target, the starting constellation has the following parameters over a 24 hour period:

- Average revisit rate = 1.67 hours
- Total time not covered = 22.46 hours over the 24 hour period
- Average pass distance of 1,286 km

The goal is then to minimize these parameters while staying within a cost bound. The problem is that changing the orbital parameters of the constellation may increase some of the parameters while decreasing others, as such it becomes a multi-objective trade space, for which the following weights were selected for each parameter:

- Weight of average revisit rate = 0.4
- Weight of total time not covered = 0.4
- Weight of average pass distance = 0.2

These weights were used in a Monte Carlo simulation to score the relative value of this constellation when moved to different orbits. Each of the values listed above was normalized to the initial constellation target observation parameters above before applying the weights to ensure that all scores are relative to the initial constellations. Scores greater than 1 mean the solution is worse than this initial case. Scores less than 1 mean the solution is better than the initial case. It is assumed that after reaching the new orbit that the spacecraft would refuel the amount of fuel they expend. While in most cases UMPIRE is used to compare refueling scenarios against non-refueling scenarios, as seen in the GEO case examined in Section 3.1, in this case it was determined that the total ΔV required to reconfigure the constellation (~500 m/s per spacecraft) would expend the majority of the fuel normally allocated for station-keeping and end of life disposal for an Earth observation spacecraft. The 24-hour time interval to observe the emergency is short enough that operational costs impacts would be negligible and therefore were not included. It is assumed that each of the spacecraft in order to rapidly respond uses chemical propellant and has a wet mass of 375 kg at the start of the retasking scenario.

When running the Monte Carlo, the orbit parameters relative to the initial constellation at 400 km and 53° are varied. To aid in finding solutions that could be ideal, the Monte Carlo altitude range was constrained from 200 km to 900 km while varying the inclination across a range of 52° to 56°. It was found in running initial cases that for the high latitude observation case with this weighting, higher altitudes and higher inclinations were generally more favorable (i.e. generally more likely to get a score less than 1 compared to lower inclinations and altitudes generally clustered above 1) thus the bias in higher altitude and inclination values in the ranges.

For each of the Monte Carlo scenarios the total cost of refueling the entire constellation back to their initial fuel total before relocating is calculated. These costs are then filtered against the desired profit of the constellation when surveying this emergency. To simplify what the maximum value of this cost can be, the total potential damage of an emergency situation will be estimated based on the $2.94B losses experienced in 1964, then adjusted for the relative population increase in Anchorage. Today that population is 288,000 but in 1964 it was ~100,000, representing an ~2.88x increase in potential losses totaling to around $8.47B. If it is assumed that the LEO constellation described above could help mitigate or recoup around 5% of the overall losses, whether it be through immediate response or targeted relief efforts and resources after the fact, then the total value of relocating the constellation for the scenario is $423.5M. If the relief effort is willing to cover roughly 10% of that potential savings the constellation could make up to $42.4M. Assuming the constellation provider desires a profit ratio >60%, the cost of refueling the constellation to support reconfiguration must be under $26.5M. This approach to the reconfiguration cost is summarized in Table 1.

Table 1. Financial Considerations Informing Cost Cap for the Monte Carlo

| Financial Consideration | Value |
|---|---|
| Total Potential Damage from Disaster | $8,470.0M |
| Percent of total damages recoverable with optimized constellation | 5% |
| Potential Damages Recoverable with Optimized Constellation | $423.5M |
| Percent of Recovered Damages to Cover Constellation Services | 10% |
| Max Cost of the Constellation Service | $42.4M |
| Desired Constellation Profit Ratio | >60% |
| **Maximum Cost of Refueling the Constellation** | **<$26.5M** |

The Monte Carlo was run for 100 iterations and scored based on the weights above. First all solutions with a normalized weighted score above 1 (meaning worse than the original constellation) were filtered out before all solutions for the cost of refueling above the cap of $26.5M were filtered out. Thus, the best solution has the minimum remaining score. This best solution had a score of 0.8087 at an altitude of 777 km and an inclination of 55.93°. Fig. 10 shows the ground track of the constellation after the reconfiguration, showing increased ground passes over the Anchorage target area compared to the baseline configuration from Fig. 8. Fig.11 then shows the pass distances with respect to Anchorage. When compared with Fig. 9 which shows the pass distance for the baseline configuration, the number of anchorage passes has increased significantly. The average distance of the passes is somewhat higher, primarily because of the increased length of the passes which produces more coverage time at larger distances.

Table 2 summarizes the change in the key performance parameters after reconfiguration of the constellation. These results represent the optimum solution for the weightings selected while respecting the cost constraints after refueling given in Table 1. At the cost of 38% greater pass distance (slightly hurting resolution), the average revisit time was halved while the overall coverage time increased over three and a half times, offering a major boon to relief efforts while suggesting that retasking cases such as these could be feasible with refueling.

While the weighting and cost values here are partly arbitrary and difficult to estimate, this retasking case shows that with the correct balance of parameters, refueling can increase the value proposition and performance for customers and their end data users. UMPIRE can help address more detailed cases with real world requirements to help reach optimum solutions for multi-objective parameter spaces such as revisit rates, pass distances, and fuel budgets against economic cost and revenue metrics and so many more to help show the benefits and potential of refueling for your mission case.

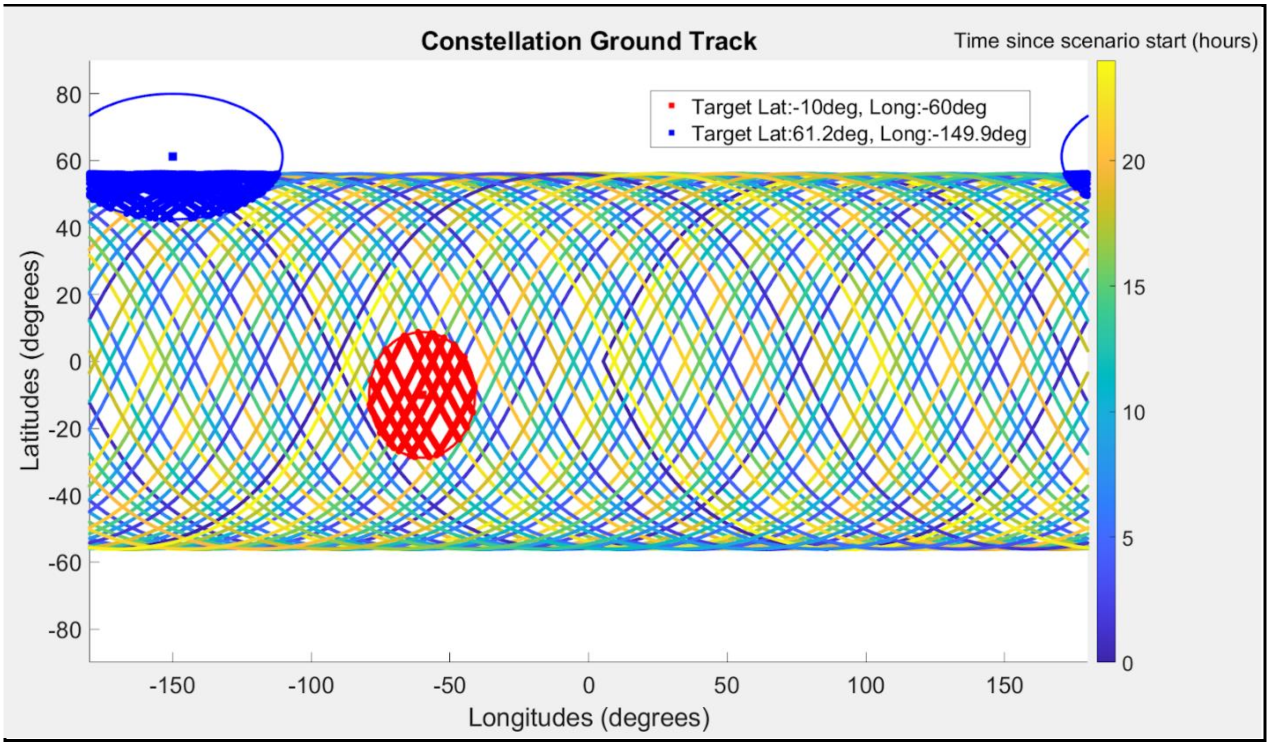

Fig. 10. Final walker delta constellation ground track including targets

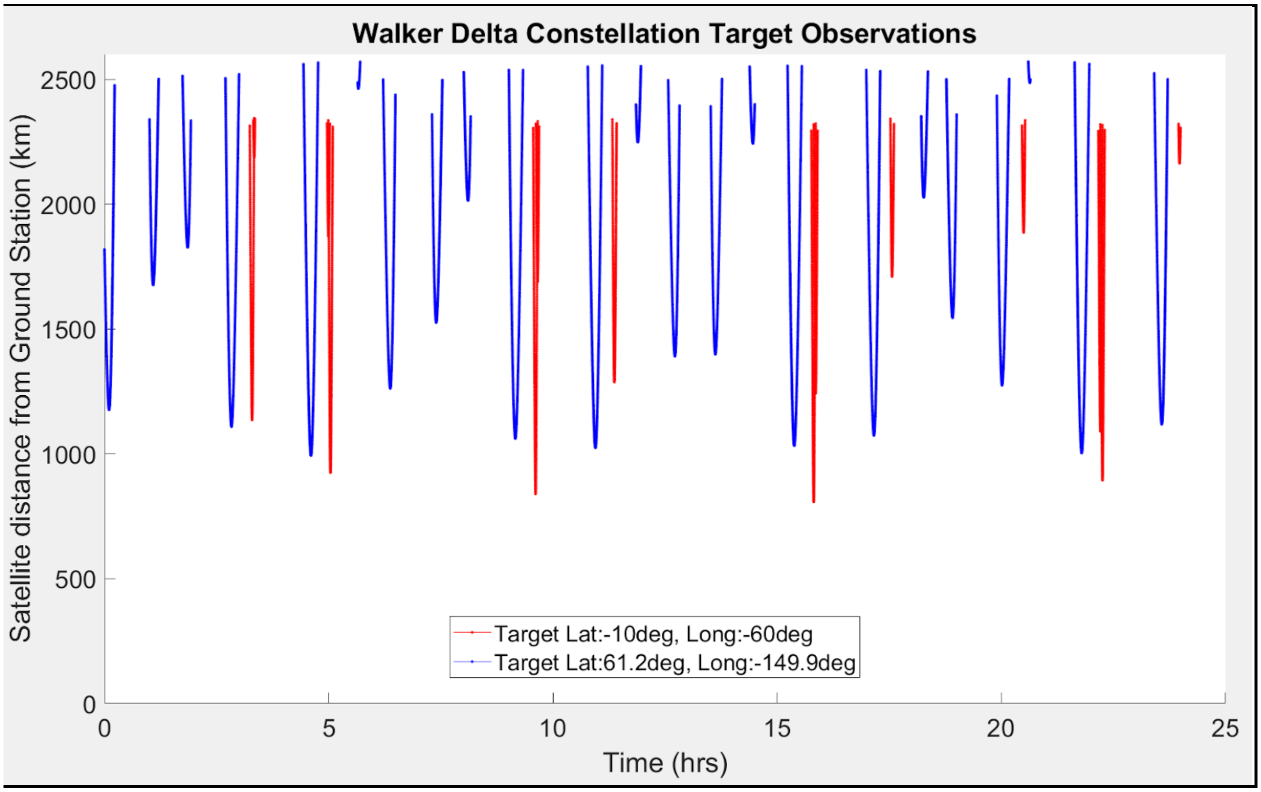

Fig. 11. Final walker delta distance from passing satellite to ground targets

Table 2. Comparison of initial and best cases showing parameter of interest changes

| | Altitude | Inclination | Average Revisit Time | Total 24hr Coverage Time | Average Pass Distance |
|---|---|---|---|---|---|
| Initial Case | 400 km | 53° | 1.67 hrs | 1.53 hrs | 1,286 km |
| Best Case | 777 km | 55.93° | 0.84 hrs | 5.38 hrs | 1,778 km |
| Change | +377 km | +2.93° | -50% | 3.52x | +38% |

### *3.3 Relocation of Satellite Servicing Vehicles between Orbit Regimes*

Satellite servicing vehicles such as Orbital Transfer Vehicles (OTVs), life extension vehicles, and active debris removal (ADR) vehicles can often struggle with the great range of potential clients who’s orbits cannot be reached by conventional fuel budgets. Refueling changes this paradigm, enabling a huge range of customers to be served within a $\Delta V$ cluster when fuel is no longer the limiting factor. One immediately valuable use case is using more fuel to enable greater relative RAAN drift rates to targets. This is relevant for all the satellite servicing cases above, particularly for reusable OTVs who may want to serve several different RAAN planes that rockets are launching to with a single asset. The $\Delta V$ versus time trades were explored heavily in previous work [11] and remain relevant to the many different LEO altitudes and inclinations of interest. Figs. 12 and 13 were generated with UMPIRE and provide a high-level overview of the $\Delta V$ versus time trades for LEO scenarios.

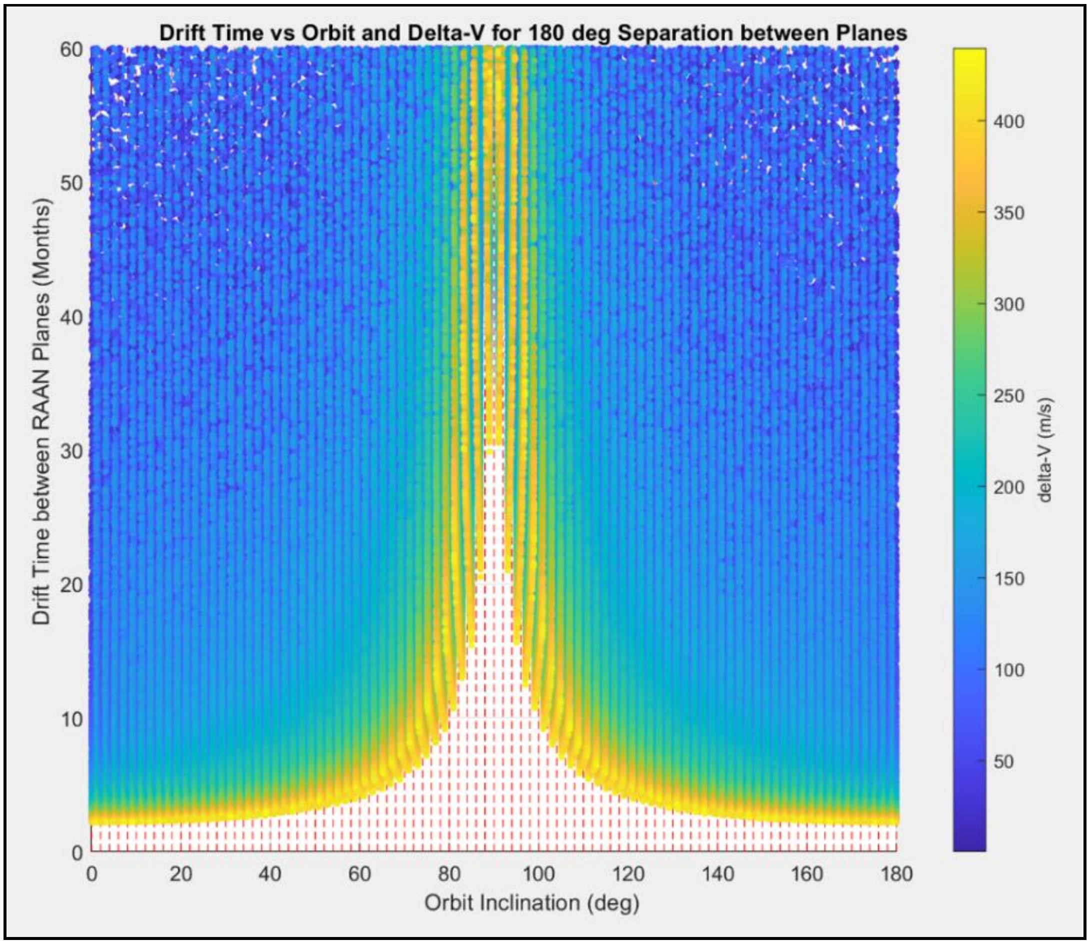

Fig. 12. Drift time vs orbit and $\Delta V$ for 180 deg separation between planes

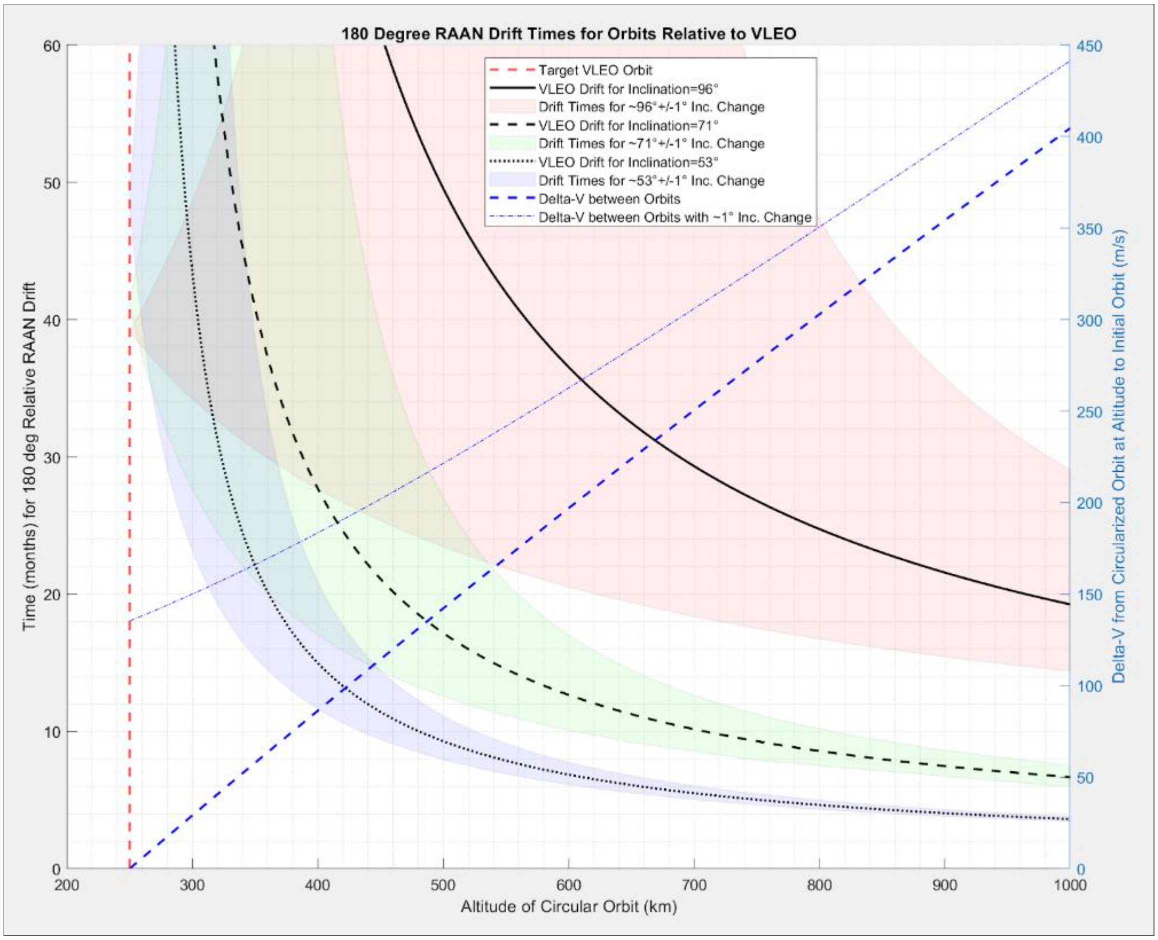

Fig. 13. Slices of drift time vs orbit and ΔV at inclinations of interest

*3.3.1 Reuse and Client Clustering to Enable Greatly Enhanced Economics*

As discussed above, one of the driving cost savings enabled by refueling in LEO is the prevention of replacement assets to meet new client needs. If clients can be clustered within several degrees of inclination of each other, the satellite servicing vehicles augmented by refueling, can be capable of serving them all without needing to launch more assets or rely upon dedicated launch option at very high costs for more exotic orbits. These trends are explored in detail in previous work by the authors presented at IAC 2022 titled ‘The Enhanced Economics, Incentives, and Multinational Cooperation Enabled by Refueling Architectures Centered Around Debris Clusters for Sustainable Active Debris Removal’ [12] exploring the cost benefit analysis of ΔV clustering debris removal targets with a comprehensive refueling constellation. While this analysis focuses on ADR missions, it is easily extensible to many other ISAM missions as they follow a similar conops where they must match orbits with a client object, complete rendezvous and proximity operations, expend some ΔV in the servicing process, and the move to the next client. UMPIRE can thusly easily apply the same analysis techniques to relocating any ISAM assets. Figs 14-16 summarize the results of the UMPIRE analysis of the ADR use case.

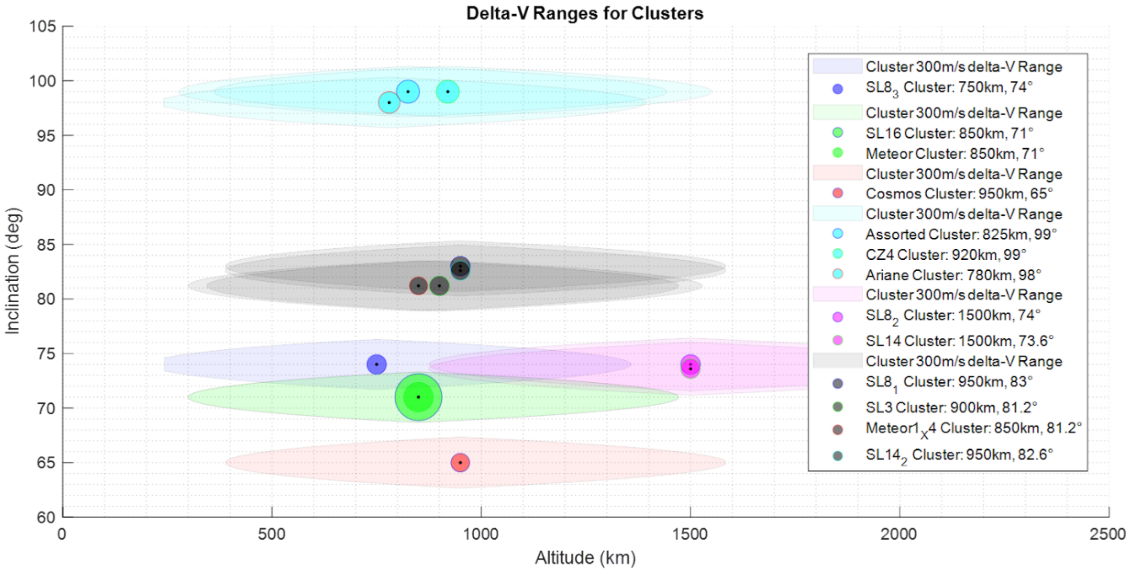

Fig. 14. Comprehensive debris removal debris clusters and ΔV ranges showing overlap

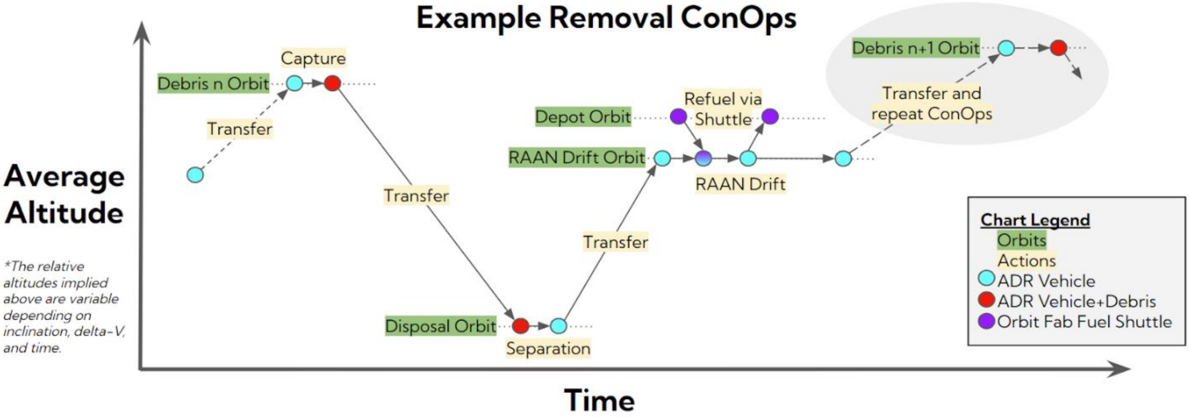

Fig. 15. Simple example of debris object removal conops within comprehensive debris removal case

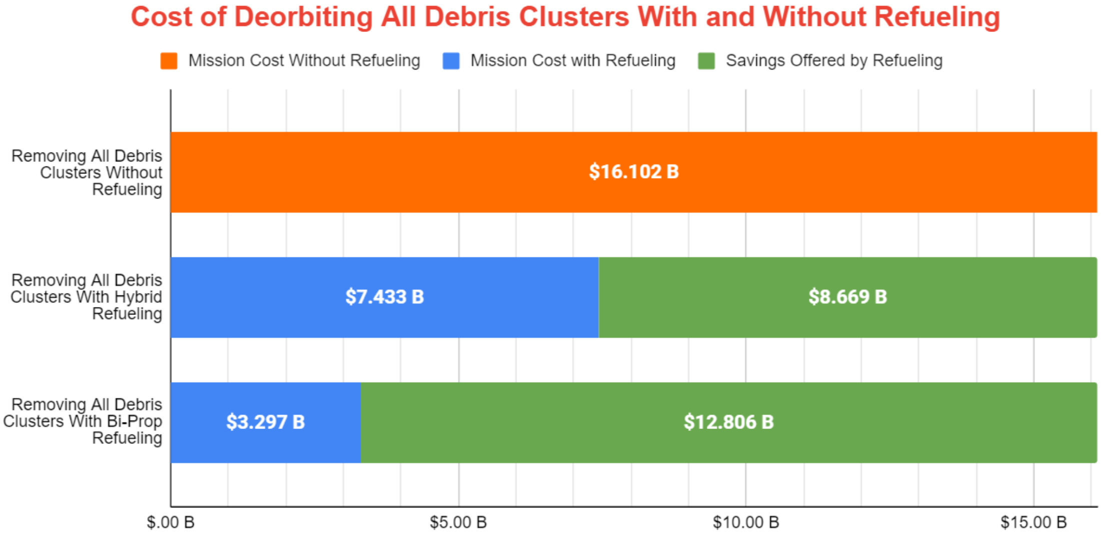

Fig. 16. Cost comparison of comprehensive debris removal approaches

For ADR, choosing an operationally flexible cost optimized solution made possible only by refueling resulted in 80% cost saving over the current state of the art. This best case is with bipropellant refueling, but by allowing the ADR vehicles to refuel after clearing out their cluster and make inclination burns to pass between the closer proximity clusters, the number of ADR vehicles could be reduced further, reducing the costs of the cost optimized third case by potentially up to another 10%. Similar gains can be expected by applying this operational flexibility through refueling to repositioning other assets in the ISAM ecosystem due to the similarities between these use cases.

## 4. Conclusion

Historically, retasking assets on-orbit has been an extremely costly trade due to the potential reduction in mission lifetime from more rapid fuel expenditure, but the advent of refueling changes this paradigm. With fuel no longer being the limiting factor on spacecraft life, capabilities of spacecraft can be dramatically enhanced dynamically in-orbit. The exact extent of the benefit refueling provides varies greatly depending on a spacecraft’s orbital regime, conops, and function. Regardless, the cases explored above show high level trades in which refueling can unlock newfound value propositions, such as GEO relocation and LEO constellation retasking, or enable missions that before would have previously been infeasible, such as comprehensive debris removal.

Across all cases, refueling offered significant cost benefits enabling greater or previously unattainable value propositions while greatly increasing asset flexibility. As it is difficult to predict when retasking may need to occur, making spacecraft refuellable in the design phase with Orbit Fab’s RAFTI can significantly decrease risk or lost revenue and increase operational flexibility if your asset or constellation ever need it. Many more potential use cases and exotic conops can be augmented or enabled by refueling and Orbit Fab has the resources to assess these diverse needs using our internal tool, UMPIRE, and our breadth of mission and architecture analysis experience.

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