Valuation of On-Orbit Servicing in Proliferated Low-Earth Orbit Constellations

Citation: Luu, Michael and Daniel E. Hastings. "Valuation of On-Orbit Servicing in Proliferated Low-Earth Orbit Constellations." Accelerating Space Commerce, Exploration, and New Discovery Conference, November 2020, virtual event, American Institute of Aeronautics and Astronautics, November 2020. © 2020 Michael Luu and Daniel Hastings

As Published: http://dx.doi.org/10.2514/6.2020-4127

Publisher: American Institute of Aeronautics and Astronautics

Persistent URL: https://hdl.handle.net/1721.1/130620

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

Valuation of On-Orbit Servicing in Proliferated Low-Earth Orbit Constellations

Michael A. Luu[1] and Daniel E. Hastings[2]
Massachusetts Institute of Technology, Cambridge, MA, 02139, United States

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

I. Nomenclature

Δv = velocity required for orbital maneuver
a = semi-major axis
CONOP = concept of operation
C_{launch} = launch cost
C_{manu} = manufacturing cost
delta-V = velocity required for orbital maneuver
e = eccentricity
g_0 = gravity
GEO = geosynchronous orbit
GPS =
h = angular momentum
i = inclination
Isp = specific impulse
J_2 = earth oblateness constant
LEO = low-earth orbit
m_0 = mass initial

---

[1] Graduate Student, Department of Aeronautics and Astronautics, and AIAA Student Member.
[2] Professor, Department of Aeronautics and Astronautics, and AIAA Fellow

m_{OOS_wet} = on-orbit servicer wet mass
m_f = mass final
n = mean motion
N = parking orbit loops for orbital phasing
OOS = on-orbit servicing/servicer
OSAM-1 = orbital servicing assembly and manufacturing 1
p = semi-latus rectum
RAAN = right ascension of the ascending node, Ω
$R_\oplus$ = earth equatorial radius
r = radius from center of the earth
r_p = radius from center of earth to apoapsis of s/c orbit
r_a = radius from center of earth to periapsis of s/c orbit
r_1 = radius from center of earth to origin orbit
r_2 = radius from center of earth to desired orbit
RPO = rendezvous proximity operations
s/c = spacecraft
μ = gravitational constant

II. Introduction

The increased access to space has contributed to increased congestion, complexity, and competition within the space market. Given this, these demand more flexible systems that can be augmented to meet the dynamic needs of the market. Once a deployed satellite runs out of fuel or malfunctions, the satellite operator's choices are to replace the satellite with a spare (stored in orbit or launched from the ground) or decommission it and wait until the entire constellation is replaced. On-Orbit Servicing (OOS) offers new flexible options by restoring service, extending operations, upgrading capabilities, mitigating risks, and managing uncertainty for future constellations. OOS encapsulates the ability for a servicing s/c to inspect, refuel, conduct maintenance, rectify anomalies, upgrade, or tug a target s/c. Being able to execute these activities permits satellite operators a plethora of options in all areas of satellite operations. This brings added flexibility to what operators may do.

Since 2007, with the success of the orbital servicing demonstration by DARPA's Orbital Express program [1], the orbital servicing industry has spawned numerous servicing missions that are beginning to enter the market. This new capability is projected to have ~4.5 billion USD cumulative revenue by 2028 [2]. With the success of Northrop Grumman's Mission Extension Vehicle, there is a proven case for OOS in geosynchronous orbits [3]. A technology demonstration mission for OOS in Low-Earth orbit (LEO) is currently being developed named OSAM-1[3] [4,5]. Extending the orbital lifetime of constellations via OOS has been shown to extend revenue production for existing constellations[6]. With the technology capability being proven, the next area of exploration of OOS in LEO would be to determine the cost-effectiveness of OOS. In this paper we analyze the cost value proposition of extending the orbital lifetime of a LEO constellation through OOS. The benefit of OOS for proliferated LEO constellations is compared to the relative cost of the alternative options – constellation replacement or deploying orbital spares.

III. Concept of Operation of OOS

From this point onward OOS will refer to an On-Orbit Servicer s/c, which is the vehicle that will interact with the target s/c. For any OOS the fundamental actions that must take place are - launch deployment, maneuver to a client satellite, conduct rendezvous proximity operations, service the client, and then maneuver to the next client.

There are three OOS CONOPs that have been proposed [7]. The first method is the most traditional, in which an OOS is launched with all servicing resources it needs carried on board, throughout all orbital maneuvers, rendezvouses, and servicing events. The second method consists of deploying depots throughout the constellation to reduce the onboard mass an OOS must carry throughout the mission. This would relieve the system requirements on the OOS as well as reduce the delta-V requirements of each orbital maneuver. The second CONOP utilizing depots

---

[3] Formerly known as Restore-L

has many considerations as it becomes a "traveling salesman" problem and is bespoke to individual cases, it will not be reviewed in this paper. Other researchers are reviewing the depot servicing model [7,8].

The third method, referred to as the "Pod CONOP", relies on a proliferated deployment and pre-positioning of all servicing resources adjacent to each target s/c in order to reduce the inert mass carried throughout the entire OOS mission. For this paper the only servicing resource being considered will be propellant, However, other servicing resources include things such as replacement parts, upgraded components, or additional payloads for client s/c. Self-contained pods designed to support extended maneuver and station keeping capabilities for client s/c are utilized to reduce the propulsion requirement of being carried throughout the entire servicing mission. The OOS system gains efficiency by having the OOS provide all robotic servicing, manipulation, and attachment of these pods to the client s/c. OOS requirements for rendezvous proximity operations (RPO), visual navigation, attitude control, and robotic manipulation are the cost drivers in manufacturing an OOS, while the inert fuel delivery to a client s/c is a driver for the mass. Separating these two functions across the OOS system enables efficiencies for manufacturing, operations, propulsion, scalability, and flexibility. The pods are cost effective by relying on the OOS for attachment rather than attaching themselves. They are equipped with basic navigation capabilities and deploy to near-adjacent orbits in the vicinity of their target s/c. The OOS first maneuvers to retrieve a pod, capture the pod, execute RPO with the client s/c, and then attaches the pod [9].

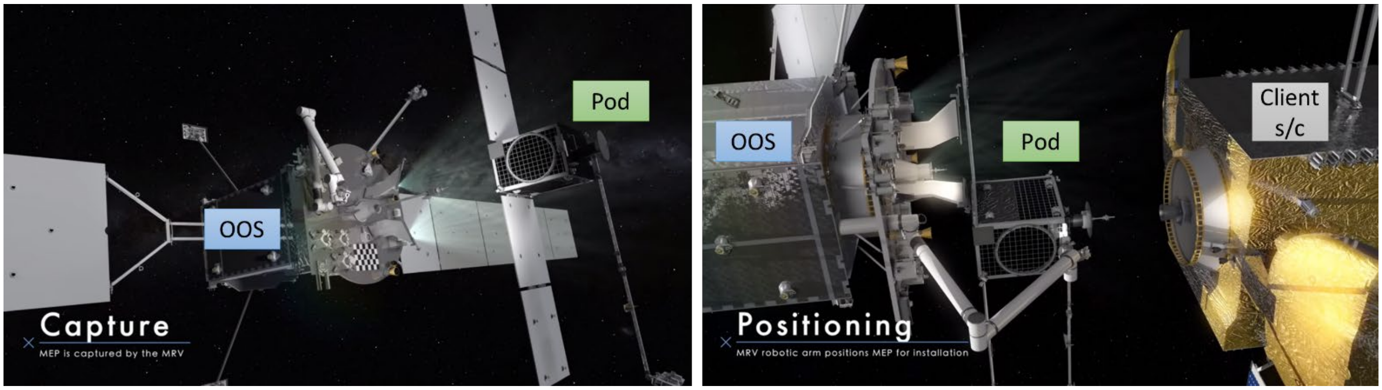

Fig. 1 Pod concept image, showing a robust robotic OOS capturing a pod (left) and attaching the pod to a client s/c (right) [10].

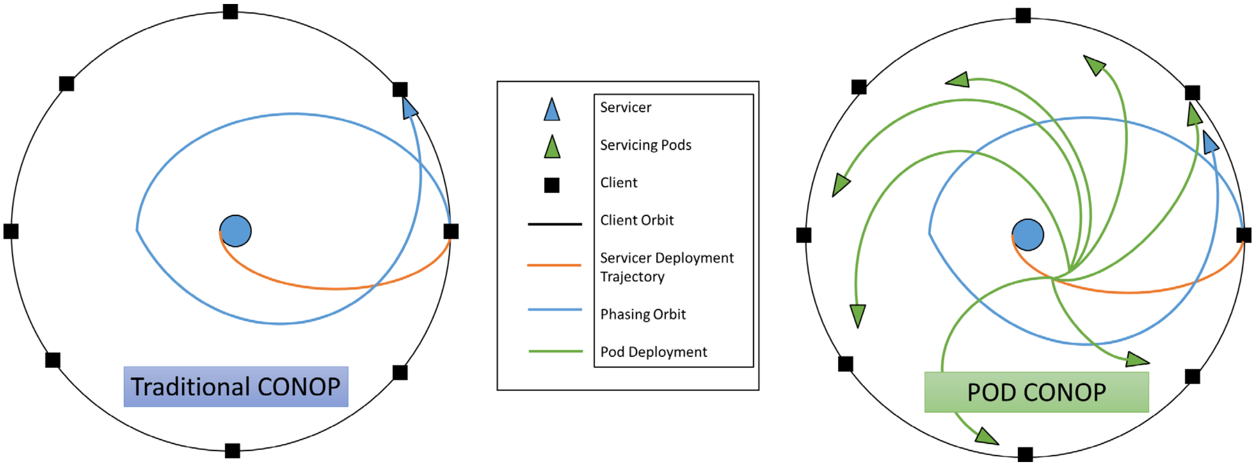

Fig. 2 Shows the difference of method one – Traditional CONOP (left) and the third method – Pod CONOP (right).

IV. Cost and Performance

A. Performance

Once an OOS is deployed it must execute three maneuvers while servicing – plane change, orbit phasing, and RPO. Delta-V and maneuver time for RPO operations are smaller in magnitude compared to the orbital maneuvers and are not considered in this paper.

1. Plane Change

First the OOS must enter the same orbital plane as the client satellite. Direct burn plane changes are too costly and expensive particularly in LEO. For this reason, we use a more economical delta-V plane change maneuver to change Right Ascension of the Ascending Node (RAAN). The earth is not a perfect sphere, it is an oblate sphere which has a larger radius around the equatorial plane where it bulges as seen in Fig. 3. As objects travel over the bulges at the equator, this changes the gravitational field that the object experiences which causes the object to drift westward [11]. This is referred to as earth's oblate J_2 perturbation. The J_2 perturbation results in westward nodal precession for objects in inclined prograde orbits.

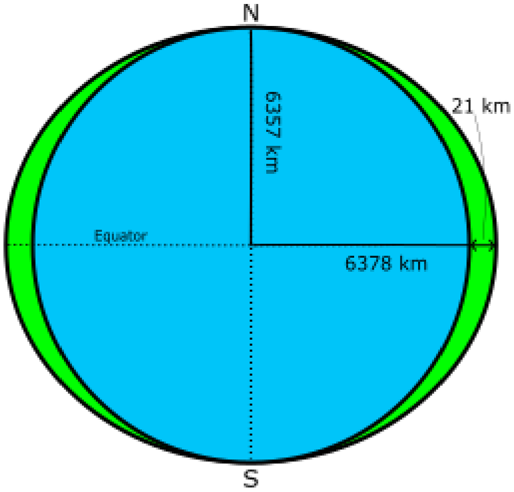

Fig. 3 Earth is an oblate sphere and not a uniform sphere. This oblateness results in the J_2 perturbation in orbital mechanics [11]**.**

The scheme for leveraging the J2 perturbation for nodal precession is shown in Fig. 4. RAAN (Ω) can be changed by adjusting your altitude. To determine $\dot{\Omega}$, the rate at which RAAN changes over time, you use the following Eqs. 1 [12,13].

$$n = \sqrt{\mu/a^3} \tag{1.1}$$

$$p = a(1-e) \tag{1.2}$$

$$\dot{\Omega} = \frac{3nR_{\oplus}^2 J_2}{2p^2}\cos i \tag{1.3}$$

Therefore, as the Δaltitude between the OOS and client satellite increases, so does the $\dot{\Omega}$. To change your RAAN at a quicker rate, you must move to a lower altitude.

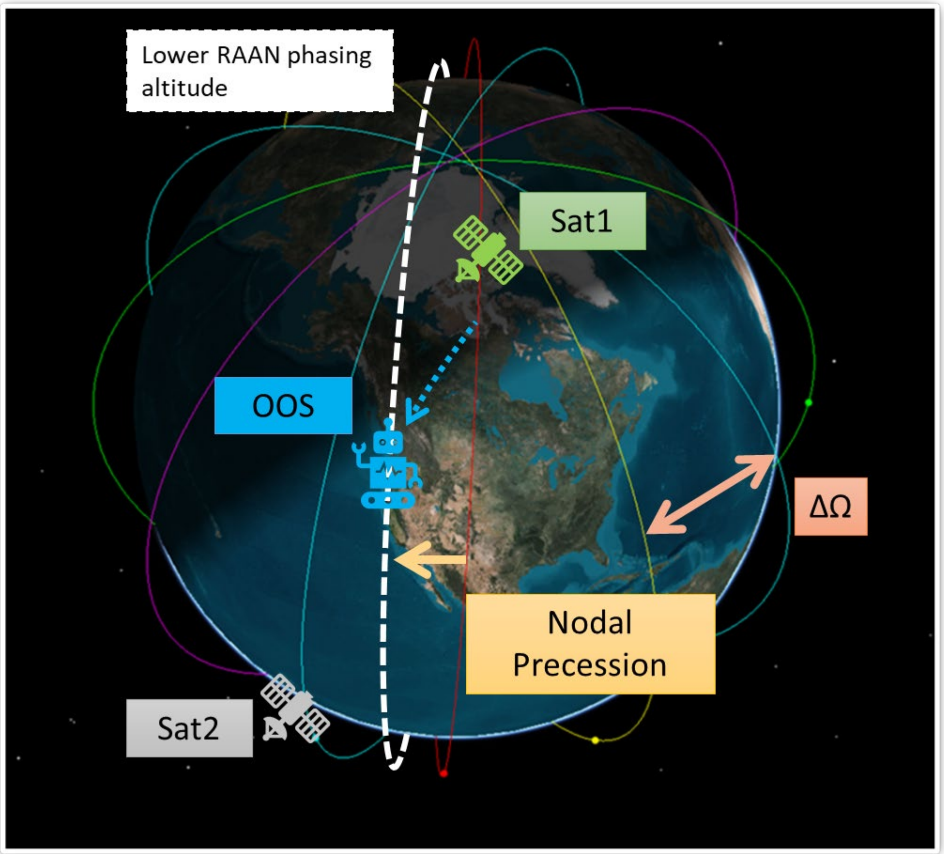

Fig. 4 As the OOS moves from Sat1 to Sat2, it executes a Hohmann transfer to a lower altitude leveraging the J_2 perturbation for the OOS to align its RAAN with Sat2, and then raise its orbit to enter the same plane.

2. Orbit Phasing

In order to align the true anomaly once the OOS and client satellite are in the same plane then the OOS must execute another Hohmann transfer to a phasing orbit which will create a difference in the orbital period for the s/c and allow them to align their true anomaly. As the timeliness or urgency of the mission varies, we can set the amount of time we would like the orbital phasing to take with Eqs. 2 to define the period of the phasing orbit. There is a constraint on the lowest phasing period which must be above 200 km, at this altitude there results in more significant orbital drag due to earth's atmosphere.

$$Period\_Client\_Satellite = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{2.1}$$

$$Phasing\_Ratio = \frac{2\pi - \Delta True\_Anomaly}{2\pi} \tag{2.2}$$

$$N = \frac{Time\_per\_Inplane\_Maneuver}{Period\_Client\_Satellite - Phasing\_Ratio + 1} \tag{2.3}$$

$$Period\_Phasing\_Orbit = \frac{Time\_per\_Inplane\_Maneuver}{N} \tag{2.4}$$

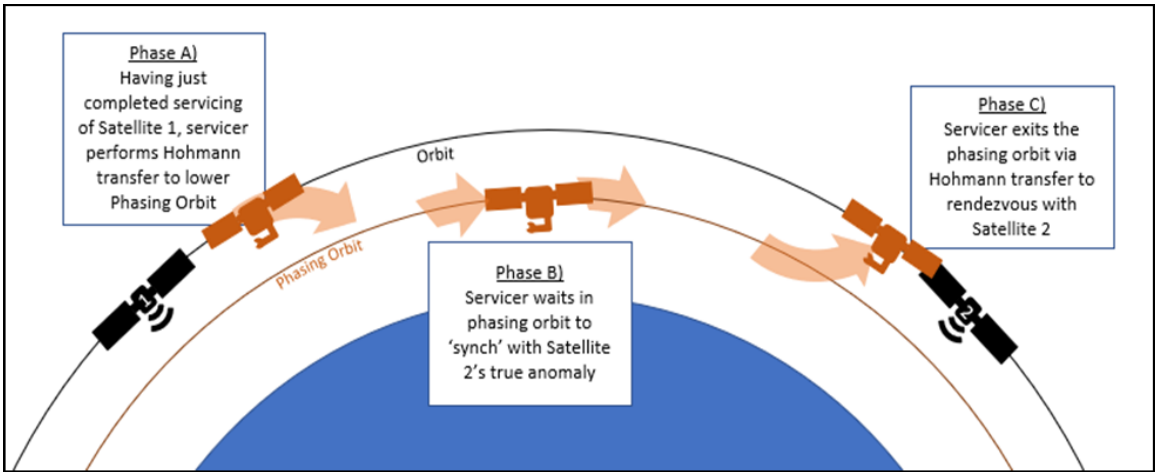

Fig. 5 Concept of operation for orbital phasing to align the true anomaly of the OOS with the client sat.

3. Time Per Maneuver

As the OOS executes a Hohmann transfer to enter the orbit phasing it requires significant delta-V to enter a lower altitude to satisfy a faster orbital phasing period as governed by Eqs. 3. As the altitude decreases for r_2, delta-V requirements exponentially increase.

$$h = \sqrt{2u}\sqrt{\frac{r_a r_p}{r_a + r_p}} \tag{3.1}$$

$$\Delta v = \frac{h_1}{r_1} - \frac{h_2}{r_2} \tag{3.2}$$

Assuming an OOS dry mass of 600 kg, an Isp of 240s, and a client altitude of 500 km. We can determine the delta_V and OOS wet mass needed for maneuvers at various time dependencies using Eq. 2 and 4.1.

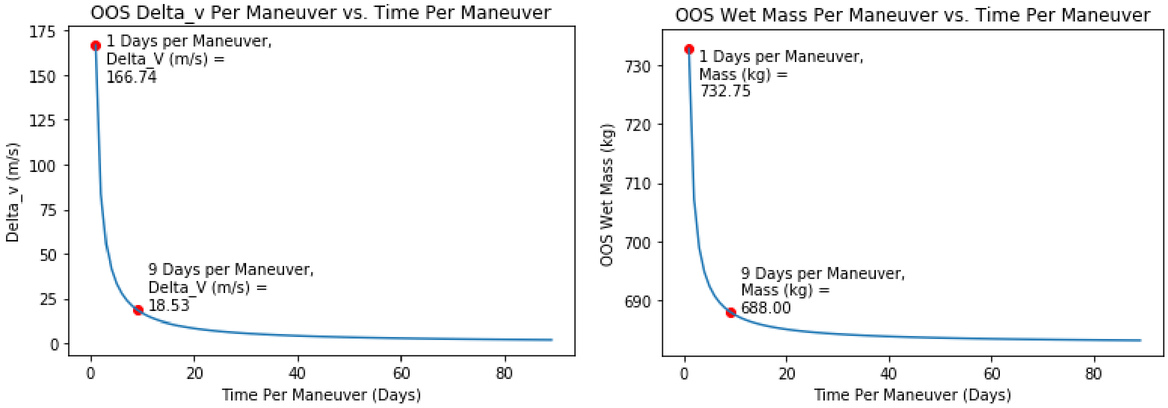

Fig. 6 OOS Delta-V required to perform a Hohmann transfer for each specified amount of days for an OOS (left). OOS wet mass required to perform the Hohmann transfer within each specified amount of days (right).

The mass of the earth creates a gravity potential well which makes it difficult for a s/c to change its orbit in LEO. The most efficient way to maneuver in this environment is with the Hohmann transfer. In Fig. 6 we see that it is exponentially more difficult to maneuver in less than 10 days at this LEO regime at 500 km. This is the "knee" in the curve where we receive less benefit for being more any more patient in our maneuver. An OOS can maneuver in less time but this will come at a severe fuel penalty and reduce the service life of the OOS, this should only be done in urgent or extreme circumstances.

V. Use Case

For the purposes of this paper we will look at a specific use case of a proliferated LEO constellation. A homogeneous target satellite constellation will be used to trade the design variables that go into the development of an OOS s/c. The target client constellation size will be varied to determine the lowest threshold of when an OOS s/c should be deployed. The spectrum of proliferation is dictated by the additional number of planes which are the constraining maneuver for the OOS compared to the in-plane maneuvers.

A. Assumptions

The client constellation consists of a proliferated LEO constellation with an inclination of 68 degrees, 0 eccentricity, altitude of 500 km, and utilizes a seven-year design life. The OOS lowers its RAAN/plane change phasing orbit to 375 km, Isp of 240s utilizing hydrazine propellant, dry mass of 600 kg, and a fuel mass delivery of 83 kg. Fuel mass is derived from the average lifetime of satellites used for station keeping in the LEO regime [13]. Each plane consists of one client satellite as this provides the greatest global ground track coverage, thus number of client planes corresponds to the total number of client s/c in the constellation. Each OOS deploys to orbit directly adjacent to the correct client plane but must execute a 180-degree true anomaly in plane transfer maneuver. This results in a worst-case scenario assumption for each subsequent plane change that the OOS must make. The RAAN change required for each maneuver divides 360 degrees by the number of planes to equally distribute the ΔRAAN between all planes.

B. CONOP Comparison – Traditional vs Pod

First, the traditional CONOP of carrying all mission resources onboard of the OOS, is compared against the alternative Pod deployment in Fig. 7. The cost model will be explained later in the paper in section VI.

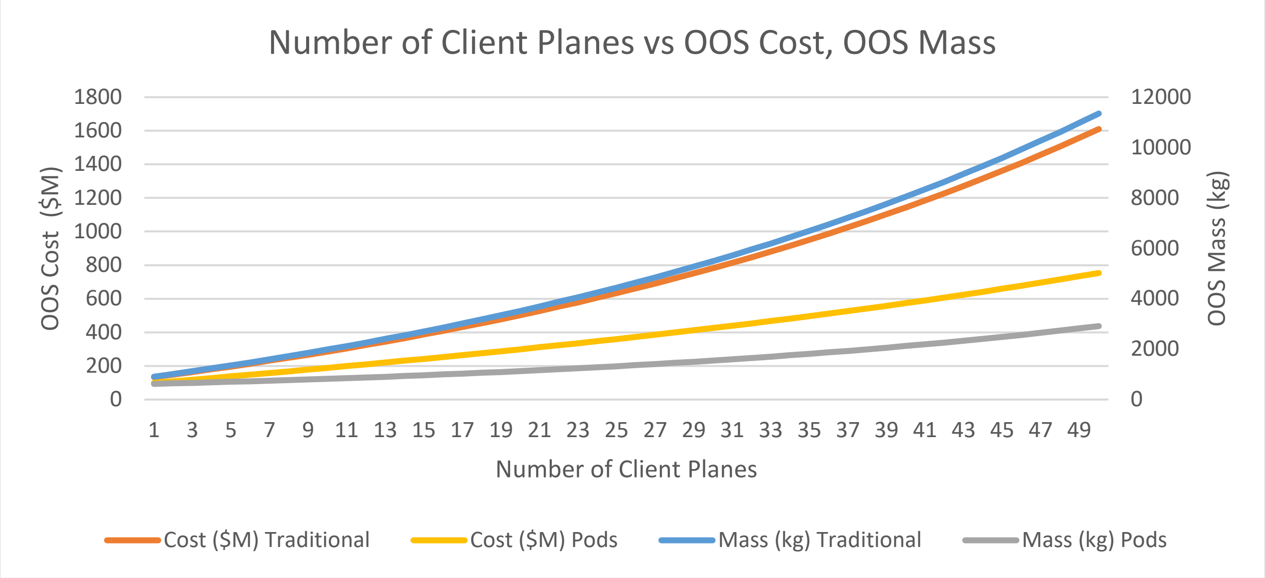

Fig. 7 As the number of planes increase, the traditional CONOP's cost and mass greatly increase compared to the Pods CONOP.

The traditional CONOP has significantly higher costs as the client constellation becomes more proliferated, this is due to the additional inert mass that the OOS must carry throughout the mission. For more sparse constellations we can see that their costs are comparatively similar. However, the mass and cost efficiencies of the pod CONOP become exponentially more advantageous as the client constellation becomes more proliferated. The pods offer more scalable technology as additional pods can be created and deployed with no change required on the OOS, whereas the traditional CONOP faces further risk, complexity, and increased requirements as the OOS wet mass grows. As an OOS wet mass and volume increases the prices increase nonlinearly due to increased subsystem requirements. This also introduces a single point of failure within the entire system if there were to be a malfunction with a single OOS. By distributing the pods throughout the constellation all servicing resources would not be reliant on a single OOS, multiple OOS could be leveraged to increase system resiliency and resource utilization. We will focus on the analysis of the pod CONOP.

C. Tradespace and considerations for pod CONOP

As an OOS system is most sensitive to the coupled design variables of timeliness, altitude, mass, and types of service. Here we expand exclusively upon the pod CONOP. The altitude for the client satellite will be varied from 500, 750, 1000, to 1500 km. We compare the servicing considerations when selecting a servicing altitude for the OOS' RAAN/plane change altitude in two cases – a static 125km lower than the client altitude, and a relative case where the OOS lowers its altitude 25% of the client altitude.

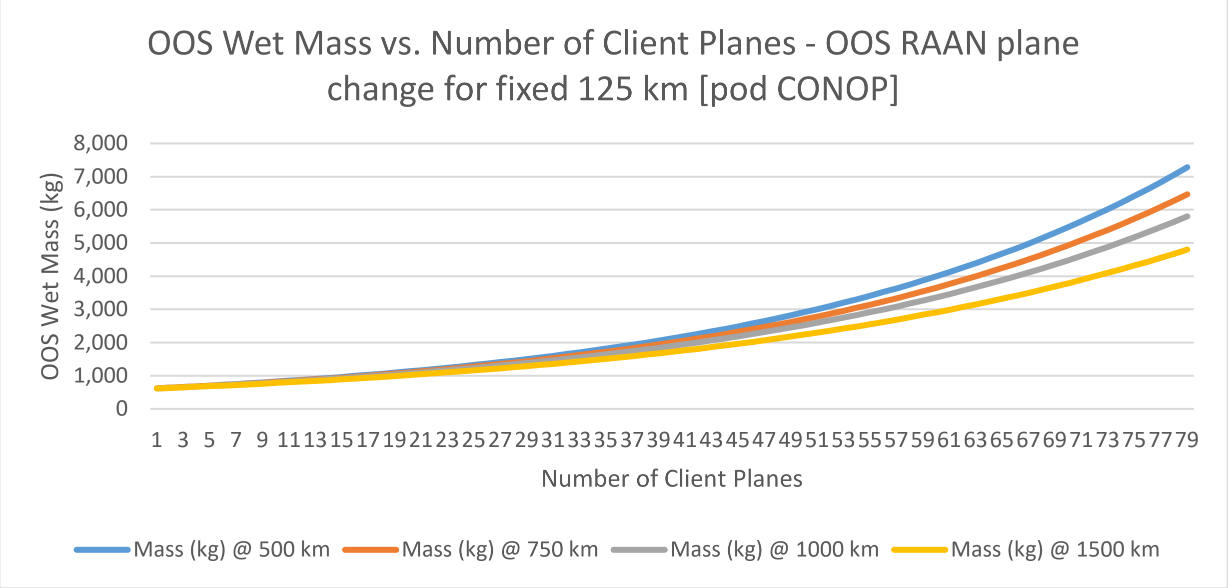

Fig. 8 OOS wet mass vs. Number of client planes, for OOS RAAN phasing orbit 125 km altitude decrease for each possible client altitude.

As the client s/c altitude increases, the OOS wet mass requirement is reduced due to decreased influence from earth's gravity well in Fig 8. This is because the 125 km decrease represents a much higher relative drop in altitude compared to the client altitude, a 25% drop for the 500 km case while it is only an 8.3% decrease in altitude for the 1,500 km client altitude case. Thus, if we want to reduce the system requirements for propulsion and OOS orbital maneuver, we should set our phasing altitude to the lowest increment possible. This design consideration favors the higher altitude 1,500 km case, however, it comes with a time penalty as we will later see. We now compare a scenario where the OOS will decrease its altitude by a relative 25% of the client altitude opposed to a static 125 km altitude drop.

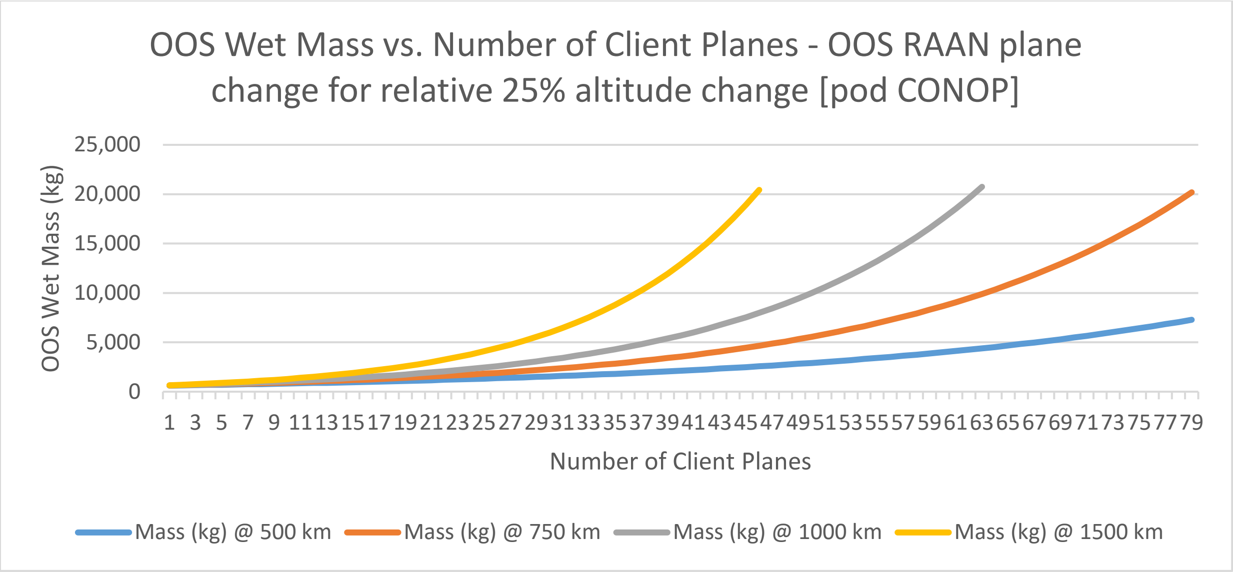

Fig. 9 OOS wet mass vs. Number of client planes, for OOS RAAN phasing orbit 25% altitude decrease for each possible client altitude.

We can see that the OOS wet mass is extremely sensitive to the RAAN phasing altitude. For the 125 km case in Fig. 8 we see that at higher altitudes, the OOS propulsive requirements are much lower resulting in an efficient servicer. However, in Fig. 9 when the OOS RAAN plane change altitude is 25% of the client altitude, we begin to get infeasible solutions as the client constellation becomes more proliferated and the OOS wet mass begins to diverge exponentially as the client altitude increases. This design consideration favors the lower 500 km client altitudes. This is due to the significant maneuver requirements of the OOS, in the 500 km case the OOS must maneuver only 125 km lower, but in the 1,500 km case the OOS must maneuver 325 km lower. There is also a benefit to considering a high relative altitude decrease that we will see in Fig. 11. We start the analysis at one plane change which accounts for an OOS inserting into the first client plane and then executing one plane change maneuver to reach the second client s/c. This is the smallest number of client planes that can exist in a constellation.

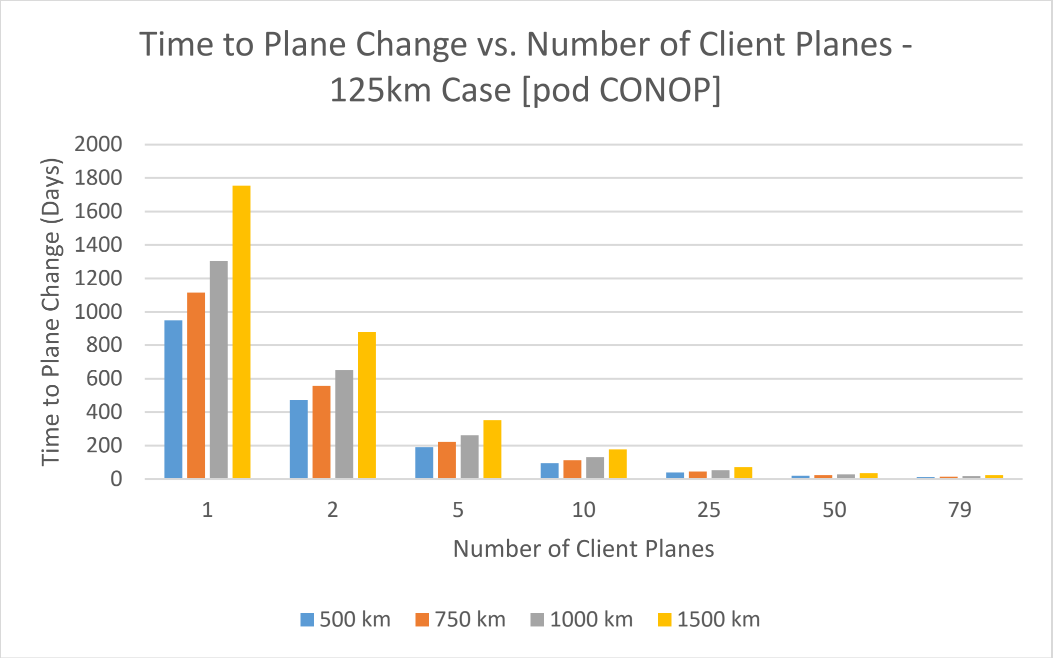

Fig. 10 Time to Plane Change vs. Number of client planes for fixed 125 km lower altitude case.

In Fig. 10 we see that setting a static 125 km decrease in the RAAN phasing altitude for the OOS results in a penalty in the servicing time for the OOS. Recall from Fig 8. that nearly the OOS wet mass and propulsion requirements were reduced, the cost of reducing the wet mass requirements comes at the expense of timeliness of service. We can see in the one to five number of client planes in Fig. 10 result in exponentially much larger servicing times at higher altitudes. However, as the client constellation becomes more proliferated. The relative impact in timeliness becomes more negligible.

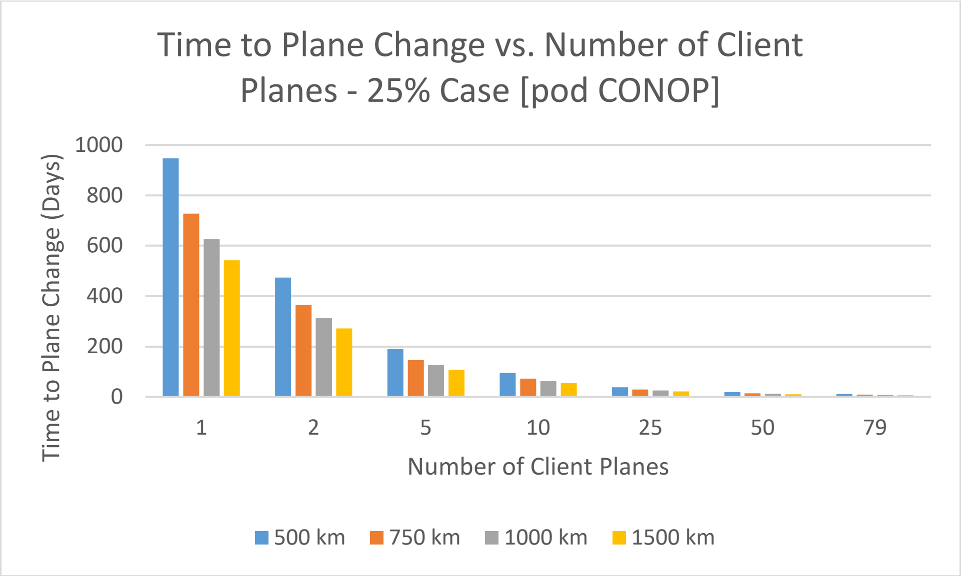

Fig. 11 Time to Plane Change vs. Number of client planes for 25% lower altitude case.

While we saw in Fig. 9 the OOS wet mass greatly increase due to the greater altitude decrease the OOS must maneuver at higher altitudes, we can see here that there is a significant time savings at the higher altitudes compared to Fig. 10. Note that in both cases the selection of phasing altitude becomes diminished at more proliferated constellations. The result shows that an OOS becomes much more resilient to design considerations at more proliferated constellations.

	Time to Plane Change (Days) - 125 km				Time to Plane Change (Days) - 25% Case			
# of planes	@ 500 km	@ 750 km	@ 1000 km	@ 15000 km	@ 500 km	@ 750 km	@ 1000 km	@ 15000 km
1	947	1114	1303	1754	947	728	626	543
2	474	557	651	877	474	364	313	271
5	189	223	261	351	189	146	125	109
10	95	111	130	175	95	73	63	54
25	38	45	52	70	38	29	25	22
50	19	22	26	35	19	15	13	11
79	12	14	16	22	12	9	8	7

Table 1 Compares the plane change time for the 125 km case and the 25% case in the pod CONOP.

In Table 1 we look at the explicit values and orders of magnitude for the timeliness of the plane change in Fig. 10 and 11. In both cases, as the client constellation becomes more proliferated, the difference in the time it takes to execute a plane change becomes much less significant across all altitude regimes.

VI. Cost Comparisons

D. Cost modeling

In order to determine the cost for the OOS, we determine the price per kg, $142M \div 1040\ kg\ =\ 0.14\ \$M/kg$, of the OSAM-1 mission [8,9]. The Δv for each maneuver will be totaled and iterated for each maneuver to provide total mass required for each OOS using the rocket Eqs. 4.

$$\Delta v = I_{sp} g_0 ln \frac{m_0}{m_f} \tag{4.1}$$

$$m_{prop} = m_0 \times e^{\left(\frac{\Delta v}{Isp*g_0}-1\right)} \tag{4.2}$$

The propellant mass is added to the OOS dry mass to calculate the OOS wet mass which is multiplied by the OOS $/kg derived from OSAM-1.

$$C_{manu} = 0.14\left(m_{OOS\_wet}\right) \tag{4.3}$$

There is the launch cost for both the OOS as well as any comparative alternative to deploy into orbit. This is derived from the Falcon Heavy with a launch capacity of 63.8 metric tons into LEO at a total launch cost of $90M. The total cost includes the cost of manufacturing and the cost of launch.

$$C_{launch} = 90\left(\frac{m_{OOS\_wet}}{63{,}800}\right) \tag{4.4}$$

The cost model for alternative options consists of calculating the total replacement cost from one client satellite to 79. This alternative option accounts for replacing satellites, building ground spares, or deploying on-orbit spares as launch costs are included. From one to 11 satellites a high-cost model is used derived from lower production earth-observation satellites such as NigeriaSat-2, Quickbird, GeoEye-1, and WorldView-2 [13]. From 12 to 79 the low-cost model derives an average satellite cost from higher production constellations - Starlink, OneWeb, RapidEye, and Iridium [16]; this model incorporates satellites that have a serial production over 11.

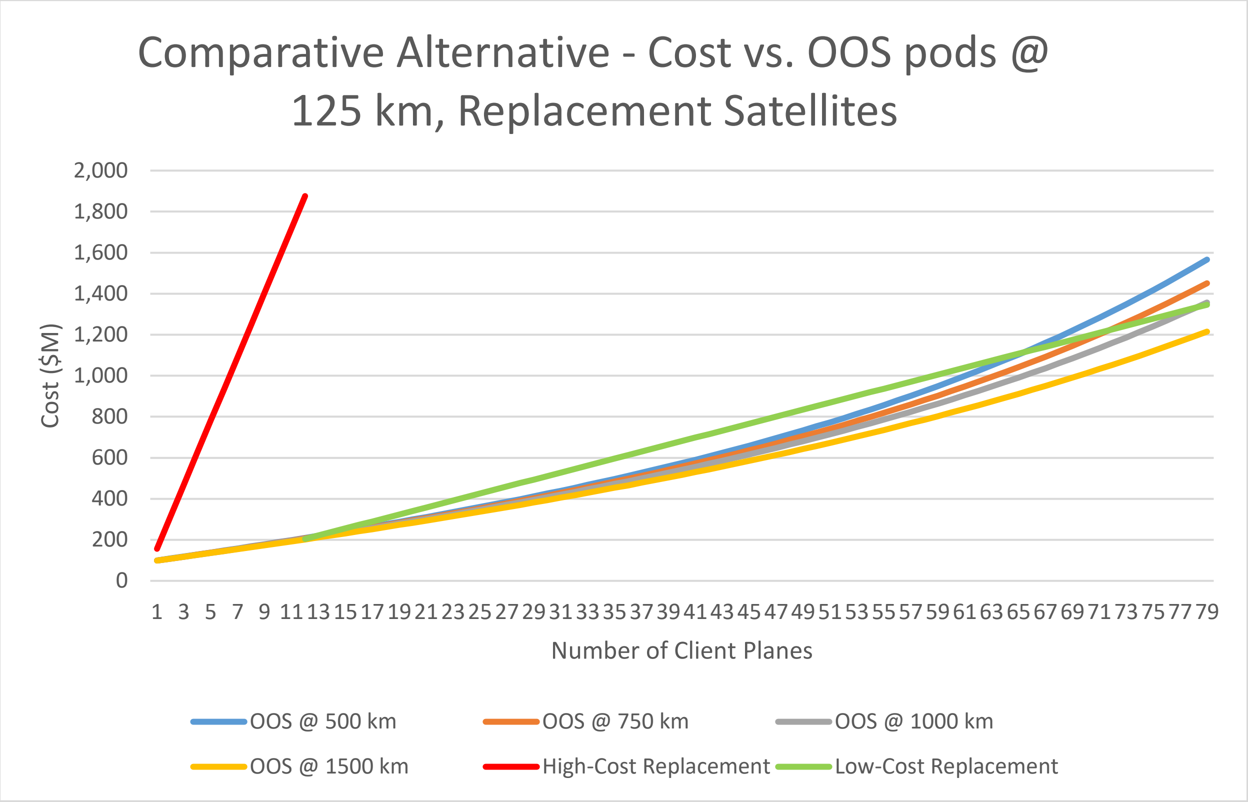

Fig. 12 Cost of OOS pod CONOP at various altitudes vs. satellite spares or deploying a replacement constellation

The replacement scenarios consider the cost for ground spares, orbital spares, and replacement constellations. Costs for manufacturing and deployment launch are also included. Operation costs are small in comparison to manufacturing and launch, they are not considered in this mode.

For the high-cost scenario in Fig. 12, it is most cost effective to service all client satellites at every altitude regime. These low-production constellations of higher cost easily provide the cost-benefit at any scenario above servicing a single client satellite. The benefit for OOS become even more beneficial considering the more exquisite payloads, resolutions, and system requirements that went into production of these satellites.

For both scenarios we see that OOS is nearly cost effective at every altitude. In the case of low-cost satellites, it remains cost advantageous to execute OOS up to ~65 satellites in the 500 km case. This is due to the OOS mass exponentially rising with the orbital phasing maneuvers representing a 25% decrease in altitude in the 500 km case but only an 8.3% decrease in altitude for the 1,500 km case. The cost for OOS in the lower altitudes could be further reduced by reducing the orbital phasing altitude to ≤ 25%. This would be a scenario where a customer was willing to be more patient and take more time to complete the OOS mission. The same could be done for the 750 km case which rises above the replacement constellation price at ~72 satellites.

There exists limited data to provide high fidelity and confidence to cost estimates to proliferated LEO constellations, as only Iridium has successfully deployed an operational proliferated LEO constellation as of yet. Additional data points for other proliferated LEO constellations including cost and s/c parameters would be needed to increase the confidence and fidelity of this analysis.

VII. Conclusion

OOS provides cost benefits in many scenarios in proliferated LEO constellations. OOS on-demand in LEO is not feasible due to orbital maneuver constraints and propulsion requirements, as in-plane maneuvers should be held to at least 10 days for efficient and economical reasons. This limitation on maneuver is suitable for scheduled servicing or scenarios where satellites show degradation through minor or intermittent malfunctions and can be queued for service. This would be similar to a situation in a car that receives a “Check Engine” or “Service Soon” indicator. On-board diagnostics could provide early notification and warning for OOS scheduling. These orbital maneuvers also do not have to be statically assigned for an OOS throughout its entire mission, an OOS can take utilize a variety of maneuvers throughout its servicing life. The OOS could also be refueled to extend its service life. This would be particularly important as OOS demand increases, adding further flexibility and options for satellite operators. While maneuvers below 10 days are taxing on the OOS they could be done on an emergency basis if a situation necessitated.

The traditional CONOP of carrying all mass on board becomes extremely cost prohibitive for multiple servicing missions compared to the pod CONOP. The pod CONOP enables the most flexibility as an OOS that can be leveraged for multiple clients and constellations as the servicing resources are now easily scalable. This also greatly reduces manufacturing, mission planning, and operation costs; as pods can be added or removed with minimal impact.

Key considerations should be made when selecting an OOS orbital maneuver for particular client altitudes between 500-1,500 km. As a client constellation is in a higher altitude, orbital maneuvers become less stressful on the OOS. However, the time to achieve those maneuvers take more time. Timeliness of service should be balanced with propulsion requirements of the OOS. But as the client constellations become more proliferated, the disparity in OOS maneuver time between altitudes becomes more negligible.

OOS is cost effective in many proliferated LEO constellations compared to the alternative to building spare or replacement satellites. A cost-effective solution can be found between for nearly all altitude regimes. This makes sense as if your vehicle ever ran out of fuel you would not throw it away. Also, if your car had a broken part you wouldn’t throwaway the whole thing in most cases. This exists for both exotic high-end cars as well as low-cost economy cars.

The recent economic downturn will likely be synonymous with reluctance to increase capital-intensive investments in the coming near-future, and this will be an issue for the space industry more than any other due to the high capital cost and risks associated with space programs. OOS can be a solution to avoid expensive deployments of new replacement constellations, extending the service life of existing constellations, pending the technology development and maturation of upcoming OOS programs. This would allow satellite operators the opportunity to increase their return on investment for deployed s/c, delay technology refresh for significant improvements, and weather times of economic uncertainty.

OOS could also be significantly more advantageous if it were adopted similar to other government provided services such as the national highway system or GPS. First, the Federal Highway Act of 1956 provided significant federal capital and investment for the creation of the national highway system which remains as the backbone of commercial infrastructure and national transportation. It has since been maintained through taxes on economic commercial activity for the service that the government provides. Secondly, the United States Department of Defense opened GPS to civilian use in 1986 [17]. The economic benefits of GPS are enormous. As NIST reports, "For the United States alone, RTI estimates that GPS has generated roughly $1.4 trillion in economic benefits (2017$) since it was made available for civilian and commercial use in the 1980s. The study authors further estimate that the loss of GPS service would average a $1 billion per-day impact to the nation." [18]. A similar model for OOS could be adopted where the government would fund the development and deployment of an OOS. Customers and commercial clients could pay the cost for deployment of a servicing pods and a marginal fee for servicing. This would significantly positively affect the ability for satellite operators to be able to achieve higher returns from their deployed satellites and reducing congestion of launching new replacement satellites. It would also provide flexible mechanisms for satellite operators to deorbit their satellites when they lose their utility.

Future work to be explored would be to create a design model to optimize OOS configuration for an explicit constellation, create higher fidelity models to include low-thrust electric propulsion, incorporate varying OOS capability by type of servicing mission, blended traditional/pod CONOPs, analyze a government funded/shared initial cost, varying the number of OOS vehicles, varying the timeliness of maneuver, incorporate varying priorities client s/c, and enumerate the design space to provide for generalized solutions.

Acknowledgments

Thanks to Sarah Morgan and Elwyn Sirieys for contributions in developing OOS evaluation tools which enhanced the analysis for this paper. This work is part of ongoing research in developing a model to optimize OOS configuration for explicit client constellations.

References

[1] Friend, R. B. "Orbital Express Program Summary and Mission Overview." *Sensors and Systems for Space Applications II*, Vol. 6958, No. April 2008, 2008, p. 695803. https://doi.org/10.1117/12.783792.

[2] NSR. *NSR Report Forecasts $4.5 Billion in Cumulative Revenues from In-Orbit Satellite Services by 2028 - NSR*.

[3] Crane, L. "Satellites Dock Together for Historic Repair Mission." *New Scientist*, Vol. 245, No. 3272, 2020, p. 13. https://doi.org/10.1016/s0262-4079(20)30481-4.

[4] OSAM-1: Robotic Servicing Mission | NASA's Exploration & In-Space Services. https://nexis.gsfc.nasa.gov/osam-1.html. Accessed Sep. 8, 2020.

[5] Reed, B. B., Smith, R. C., and Naasz, B. "The Restore - L Servicing Mission." No. September, 2016, pp. 1–8. https://doi.org/10.2514/6.2016-5478.

[6] Graham, A. R., and Kingston, J. "Assessment of the Commercial Viability of Selected Options for On-Orbit Servicing (OOS)." *Acta Astronautica*, Vol. 117, 2015, pp. 38–48. https://doi.org/10.1016/j.actaastro.2015.07.023.

[7] Ho, K., Wang, H., DeTrempe, P. A., du Jonchay, T. S., and Tomita, K. "Semi-Analytical Model for Design and Analysis of On-Orbit Servicing Architecture." *Journal of Spacecraft and Rockets*, 2020, pp. 0–0. https://doi.org/10.2514/1.A34663.

[8] Zhu, X., Chen, J., Zhang, C., and Qiao, B. "Optimal Fuel Station Arrangement for Multiple GEO Spacecraft Refueling Mission." *Advances in Space Research*, Vol. 66, No. 8, 2020, pp. 1924–1936. https://doi.org/10.1016/j.asr.2020.07.028.

[9] Space Logistics Services – Northrop Grumman. *MEP, pods, mission extension.* https://www.northropgrumman.com/space/space-logistics-services/. Accessed Sep. 23, 2020.

[10] Northrop Grumman's Mission Extension Pods (MEPs) - YouTube. Northrop Grumman, 2019.

[11] J2 Perturbation. https://ai-solutions.com/_freeflyeruniversityguide/j2_perturbation.htm. Accessed Sep. 23, 2020.

[12] Wertz, J. R., Collins, J. T., Dawson, S., Königsmann, H. J., and Potterveld, C. W. Autonomous Constellation Maintenance. Springer, Dordrecht, 1998, pp. 263–273.

[13] Legge, Robert S., J. *Optimization and Valuation of Recongurable Satellite Constellations under Uncertainty*. Massachusetts Institute of Technology, 2014.

[14] Maxar Technologies Inc. - NASA Selects Maxar to Build, Fly Innovative Robotic Spacecraft Assembly Technology on Restore-L. https://investor.maxar.com/investor-news/press-release-details/2020/NASA-Selects-Maxar-to-Build-Fly-Innovative-Robotic-Spacecraft-Assembly-Technology-on-Restore-L/default.aspx. Accessed Sep. 9, 2020.

[15] Ticker, R. Restore-L Mission Information. 1–9. http://ssco.gsfc.nasa.gov/. Accessed Sep. 9, 2020.

[16] Wang, B. SpaceX Starlink Satellites Could Cost $250,000 Each and Falcon 9 Costs Less than $30 Million | NextBigFuture.Com. *Next Big Future*. https://www.nextbigfuture.com/2019/12/spacex-starlink-satellites-cost-well-below-500000-each-and-falcon-9-launches-less-than-30-million.html. Accessed Sep. 24, 2020.

[17] Juquai McDuffie. Why the Military Released GPS to the Public. *Popular Mechanics*. 1. https://www.popularmechanics.com/technology/gadgets/a26980/why-the-military-released-gps-to-the-public/. Accessed Sep. 28, 2020.

[18] McTigue, K. Economic Benefits of the Global Positioning System to the U.S. Private Sector Study. https://www.nist.gov/news-events/news/2019/10/economic-benefits-global-positioning-system-us-private-sector-study. Accessed Sep. 28, 2020.