Payload and Constellation Design for a Solar Exclusion-Avoiding Cislunar SSA Fleet

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1. ABSTRACT SUMMARY

As the predicted and realized volume of governmental and commercial activity in orbit continues to grow, the number of regimes in which activity can be found may similarly be expected to increase. As an example, plans for activity in the cislunar regime are being developed in growing depth [1].

The cislunar regime may be thought of as the region extending from above the Geosynchronous Earth Orbit (GEO) neighborhood – near stationary orbit altitude – to the Lagrange point on the far side of Luna, Earth's moon, but a few key loci in this regime will be more populated than others. Near-rectilinear halo orbits (NRHOs) provide relative stability near Luna itself, as do two of the aligned Lagrange points (L1 and L2), and the L4 and L5 points provide long-term orbital stability as well as comparatively simple access to solar power. These loci, all of which are possible locations for a lunar gateway station or long-term scientific emplacements, and all transit routes and communications relay sites linking these loci, may be of critical interest for a successful expansion of human economic activity into the trillion-dollar opportunity that the near-term future in space represents.

As such, it will be very important to maintain space situational awareness (SSA) overwatch on these loci and the routes and links connecting them, to preserve investments made and protect the activity these infrastructure elements support. A key part of this overwatch will be maintaining custody of objects in this regime, including active objects and any debris, to support appropriate traffic management. This overwatch should be maintained persistently, to avoid situations where collisions are not detected until after they become unavoidable.

Because the cislunar regime includes regions which are extremely distant from the surface of the Earth, it is challenging to use radar systems to track smaller objects there. Optical and infrared systems face the challenge of solar and lunar exclusions, when bright emissions or reflections from astronomical bodies can obscure the space objects in this regime. Given these physical limitations, the most viable solution is to operate a ground network supplemented by spaceborne sensors. As commercial SSA networks continue to proliferate and supplement government sensors, the physical limitations will be minimized but not fully defeated. Flying sensors in space can completely eliminate astronomical body exclusions (including lunar and solar exclusions) through clever constellation design, which may include the use of sensors at Lagrange points, in GEO, or in highly elliptical orbits with apogees at multiple of the GEO radius (called high orbits with profound eccentricity, or HOPE trajectories), and can also address range limitations by approaching Luna more closely than the Earth's surface ever does.

This paper will focus on the initial analysis and design of a sensor payload which can operate from orbit to support a cislunar SSA network, flying in a constellation uniquely designed to deliver constant coverage while requiring the smallest amount of cost outlay. Such a payload, if matched to the appropriate sensor network design, could offer protective overwatch to the extensive orbital infrastructure that the cislunar regime may soon contain. First, the utility of HOPE orbits in providing visibility to key loci in the cislunar regime is modeled. Second, first-order cost estimates for commercial-grade (i.e., non-exquisite) spaceborne and ground-based sensors are generated and compared, and finally an assessment of the relative sizes of the ground arm and spaceborne arm of a hybrid sensor network is combined with a simple commonality analysis to determine opportunities for cost savings.

2. INTRODUCTION

As interest in spaceborne activity, especially commercial activity, rises, so eventually will the volume in which such activity occurs. To date, human activity in the form of exploration or scientific research has extended from the upper edge of the stratosphere to the innermost of the minor planets of the solar system, although human presence itself has not physically stretched beyond Low Lunar Orbit (LLO). While extensive new activity can be expected in Low Earth Orbit (LEO), there is in fact limited volume around the Earth, and some advantages to operating in or traversing the volumes of space extending much further than those traditionally accessed.

Space activity near the Earth may be designated into one of five categories: LEO, Medium Earth Orbit (MEO), High Earth Orbit (HEO), Geosynchronous Earth Orbit (GEO), and extra-GEO or trans-GEO (denoted X-GEO). In LEO, where the greatest density increase in traffic is expected, most systems serve to relay communications or collect imagery. Sandbox-level experimental systems and a large amount of human traffic may also be found somewhere in this regime. Satellites in MEO almost exclusively serve for Positioning, Navigation, and Timing (PNT) infrastructural purposes. Systems in GEO operate as large-field-of-view imagery collectors or global communications relays, and HEO systems often fill specialty support roles, such as collecting imagery or providing communications for high latitudes. Accordingly, the cislunar portion of the X-GEO regime (above GEO but near the lunar orbit radius; i.e. not extending beyond orbits captured by the Earth-Moon system), occupied presently by interplanetary exploration systems, advanced astronomical survey systems (NASA space telescopes), and little else save for discarded upper stages, has the most room for additional activity, given that it includes a physical volume 1000 times the volume of the current utilized cis-GEO region.

Fig. 1 illustrates some of the potential for human economic activity in the various regions of the cislunar volume, focusing on but not strictly limited to the Lagrange points. Note the wide array of industries represented.

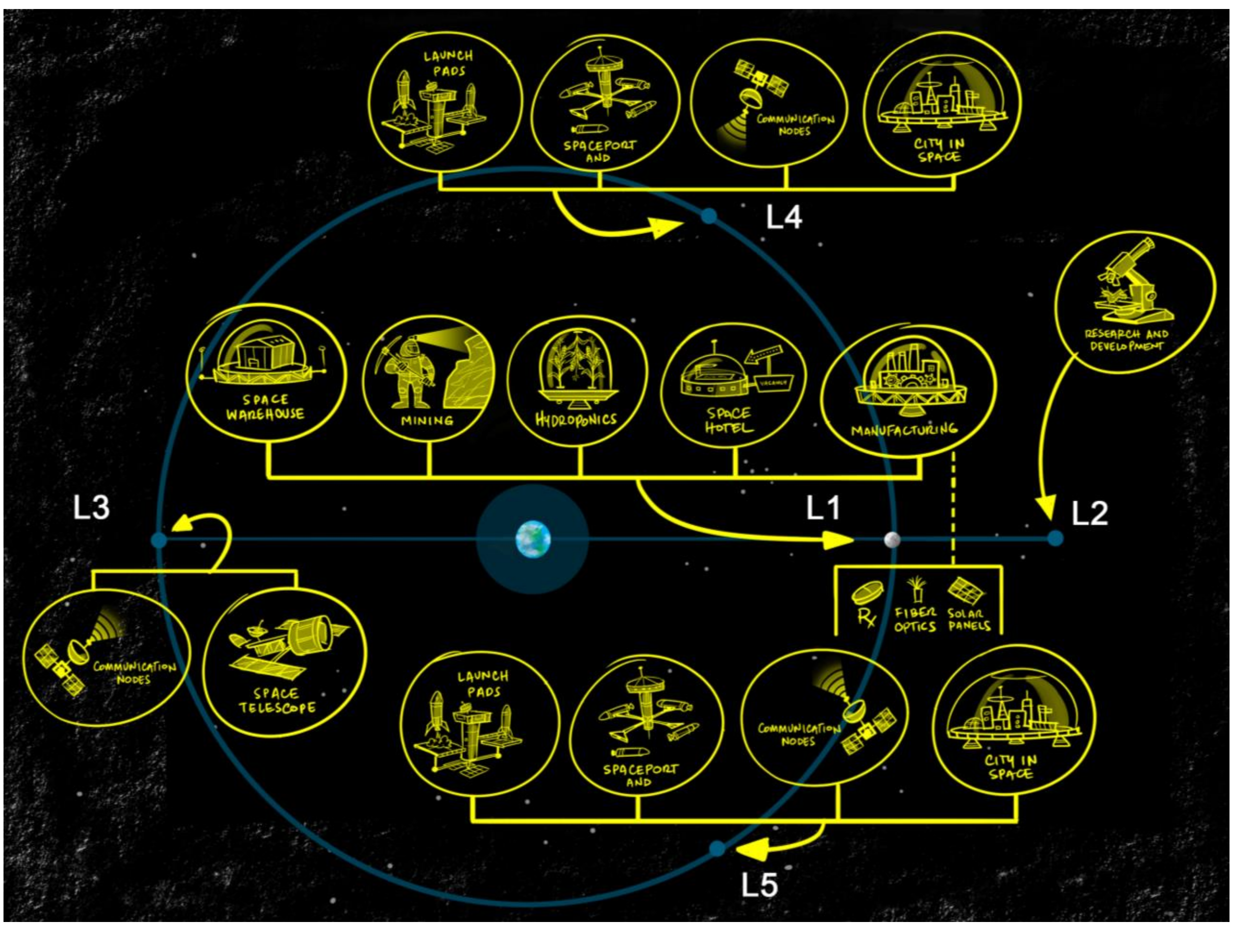

Fig. 1. Artist's Concept[i] Map of Potential Economic Activities in the Cislunar Regime.

Because careful watch of such activity (which has been predicted to grow into a trillion dollars' worth of interaction [2] in the coming decades) is a desirable precursor, creating sensor architectures able to maintain persistent custody and enabling associated Space Traffic Management (STM) actions is an immediate goal.

3. APPROACH TO MAINTAINING CUSTODY

The general problem of maintaining custody of a resident space object (RSO) may be defined as collecting observations of the RSO with a cadence such that knowledge of its current state and projected future state is available within limited uncertainty boundaries. While this may be strictly mathematically defined such that cones of future position never grow beyond a given size, a good heuristic for custody is that an RSO be observed sufficiently often that it cannot perform any major behaviors without notice by the observing party. E.g., an RSO will not have time between subsequent observations to complete major maneuvers, nor to come into near proximity of another RSO, nor to perform such actions as deploying/recovering sub-satellites [3].

All of these guidelines can be converted into temporal observation cadence requirements; for instance, for an RSO in an uncluttered orbit and with limited maneuvering capacity, the ceiling for observations may be as infrequent as one per quarter-orbit. Maintaining custody then is a problem which is driven by the need to operate sensors such that a certain number may always contain the target loci. This problem may require multiple sensors to admit a solution, and must account for physical constraints. The chief constraint on maintaining a sensor field of view upon target loci in the cislunar regime is the need to account for the bright background emitted by the Sun as the Earth and the Moon traverse their regular courses about it. The Sun emits (and the Moon reflects) across the spectrum, and background noise can hide smaller objects. This state is known as a solar exclusion, when the bright Sun (or reflected Sun) hides an RSO. Similarly, occlusion, when an RSO passes behind the Earth or the Moon itself and thus is not in a direct line of sight, can also hide RSOs. This paper is chiefly concerned with means of deploying sensors such that periods of occlusion or Solar exclusion do not affect the ability of a sensor network to maintain custody of RSOs in prime cislunar loci.

To address this concern, three factors are considered. The first factor is the design of unique orbits, specifically HOPE trajectories, for spaceborne observation constellations, such that occlusion and exclusion are reduced or eliminated to the greatest possible extent. The second factor is the combination of spaceborne sensors with a ground observation network, and the third factor is the design of a sensor payload such that hardware and software commonality between ground-based and spaceborne systems is increased to a point allowing for cost savings. Each subsection below addresses one of these factors.

3.1 Mechanics of Solar Exclusion and Planetary Occlusion and Spaceborne Avoidance Thereof

The straightforward representation of the geometry of the cislunar regime is as below in Fig. 2:

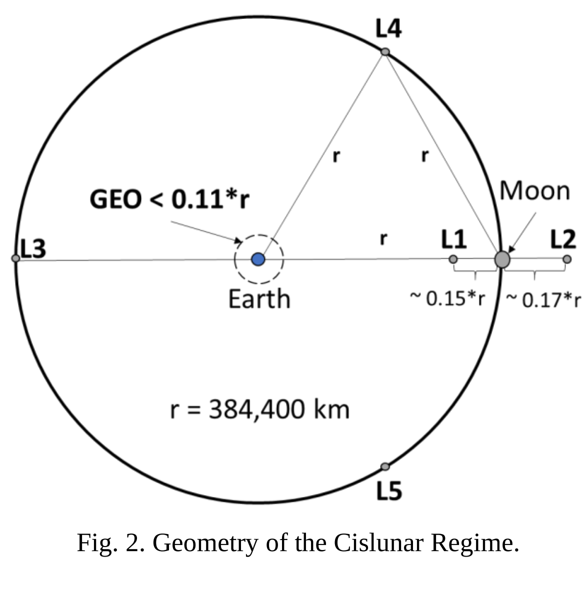

Fig. 2. Geometry of the Cislunar Regime.

There are several potential solutions to the problem of full sensor coverage of the cislunar volume. One such entails posting sensors at the L4 and L5 points; however, these loci are also highly desirable as space for clustered economic activity, and it may not be desirable to place STM sensors in orbital slots which might require frequent maneuvers or be subject to high potential for radio interference. Another interesting solution is emplacing two spaceborne sensors in HOPE trajectories [4] around the Earth, which traverse to apogees of several multiples of the GEO radius with very high eccentricity, essentially obtaining enough orthogonal standoff distance from the Earth-Moon line that even a direct alignment of the Sun on this line will not exclude a sensor at a HOPE apogee from looking closely at the libration (or Lagrange) points. HOPE orbits may also be tilted with apogees out of the plane of the ecliptic to limit other interfering factors, although relying solely on spaceborne sensors may result in increased duty requirements on them and shortened operational lifetimes.

A clear solution is a hybrid network, with some sensors placed on the Earth's surface and some operating from orbit. Of these, high orbit is likely preferred. Given that determination of a spacecraft's state following a maneuver or anomaly is of critical importance, the rate at which this can be achieved is paramount. As is well known, using a single sensor on the ground to determine the orbit of an RSO in the geocentric regime requires the largest amount of time due to the need to wait for the space object to traverse enough of an arc to support well-conditioned solutions. More rapid solutions are achieved when distributed networks apply instantaneous geometric diversity to enable a well-behaved solution without requiring the spacecraft to travel great distances taking valuable time. While this can be achieved solely by a ground network of telescopes for the geocentric regime, it is important to note that the effective geometric diversity of a ground-only solution for the cislunar regime is significantly impacted by the factor of ten increase in range. Augmenting ground networks with space-based systems in high orbits will effectively address this challenge.

Sensors in HOPE trajectories, with high eccentricity and concomitantly high hangtimes near apogee, are thus a viable way to address the need for persistent cislunar coverage. Fig. 3 illustrates a reference case for the evaluation of the achievable coverage of a pair of HOPE orbits observing RSOs located at each of the Colinear Libration Points (L1, L2, L3) in cislunar space. This instantaneous representation shows the sun vector in the direction of the moon which is consistent with a new moon phase; however as time progresses, this vector rotates about the axis containing the apogees of both spacecraft (the direction perpendicular to the ecliptic plane, nearly polar in respect to the Earth).

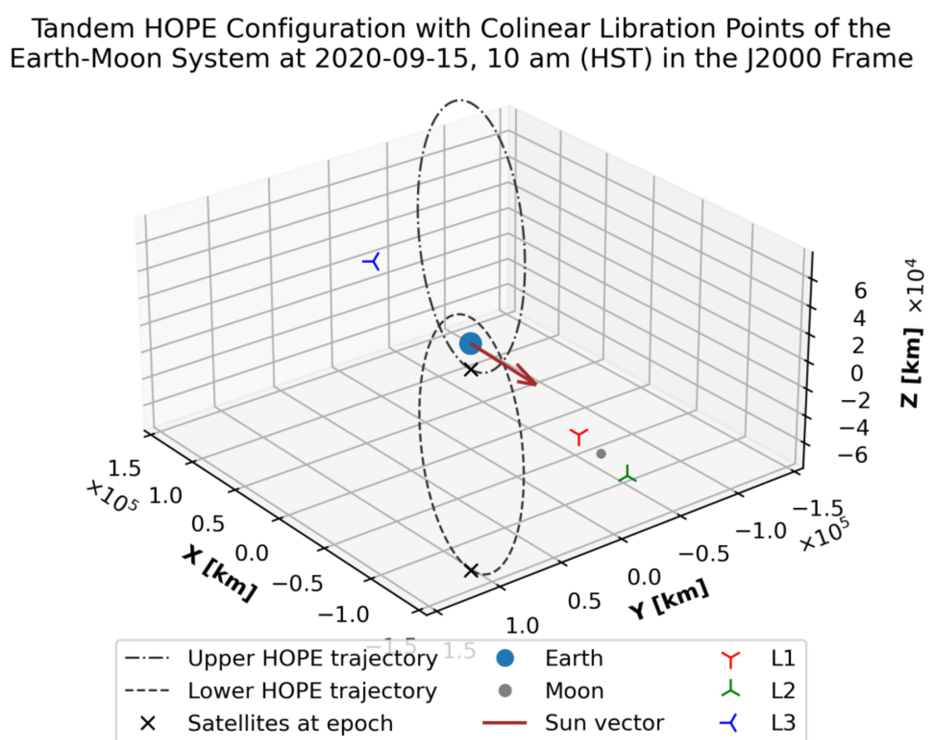

Fig. 3. HOPE Orbital Map with Colinear Points.

Fig. 3 indicates the positions of sensor satellites in two HOPE trajectories, with apogee 172,000 km (approximately 4.07 GEO radii). Note the trajectories are phased such that one sensor is near apogee, enjoying an extended hangtime, while the other passes perigee. This phasing helps to ensure that one or the other sensor is almost always at apogee, and therefore potentially able to avoid the solar exclusion due to its orthogonal offset, at all times.

As a first-order approximation of the projected activity about the libration points of interest, especially pertaining to the captured orbits thereof, a visibility assessment was undertaken with three sets of 10,000 discrete points. These were randomly sampled at every time step from a multivariate Gaussian having a variance of 10×10^8 km^2 along each dimension and mean values at the respective Lagrange stations, the locations of which were dynamically scaled according to the instantaneous offset between the earth and moon. The minimum distances from the center of the considered excluding/occluding bodies and the line of sight vectors were determined according to the following equation. Here, the vector $\overrightarrow{SP}$ extends from the satellite of interest to the observed point, $\boldsymbol{i}$, and $\overrightarrow{SB}$ from the satellite to the center of the obscuring body, B, while the enclosed inner product is necessarily positive.

$$d_{\min}^{(i,B)} = \|\overrightarrow{SB}\| \sin\left\{\cos^{-1}\left(\frac{\overrightarrow{SP}\cdot\overrightarrow{SB}}{\|\overrightarrow{SP}\|\|\overrightarrow{SB}\|}\right)\right\}$$

Where $d_{\min}^{(i,\,\mathrm{luna})}$ was found to be within 5% of the mean radius of the moon, the latter was marked as an offending body for the associated point and visibility was deemed not possible. In the rare case where the candidate point resided within the lunar sphere, it was discarded from the analysis. Following this, and although precise determination of the solar exclusion phenomenon may largely depend on capabilities of the employed observation hardware, the assumption was made that points with a projected line-of-sight vector outside a sphere 10X that of the radius of the sun would be safe to consider "observed." Calculating for every candidate point at each time step enabled a time history to be developed for the percentage of points determined to be within view for each spacecraft.

Given their proximity to the moon and alignment with the Moon and Earth as occluding bodies, we expect the colinear Lagrange points to have the most significant periods of lunar and solar exclusions. Fig. 4 illustrates this phenomenon over an orbital period of the observing spacecraft, where a dip in visibility of the regions centered on each Lagrange point occurs as a function of time. Notice that the tandem design and phasing of the two satellites in opposing HOPE orbits enables each spacecraft to complement each other, providing near-complete visibility of the region at a time when the other satellite experiences its degradation in coverage.

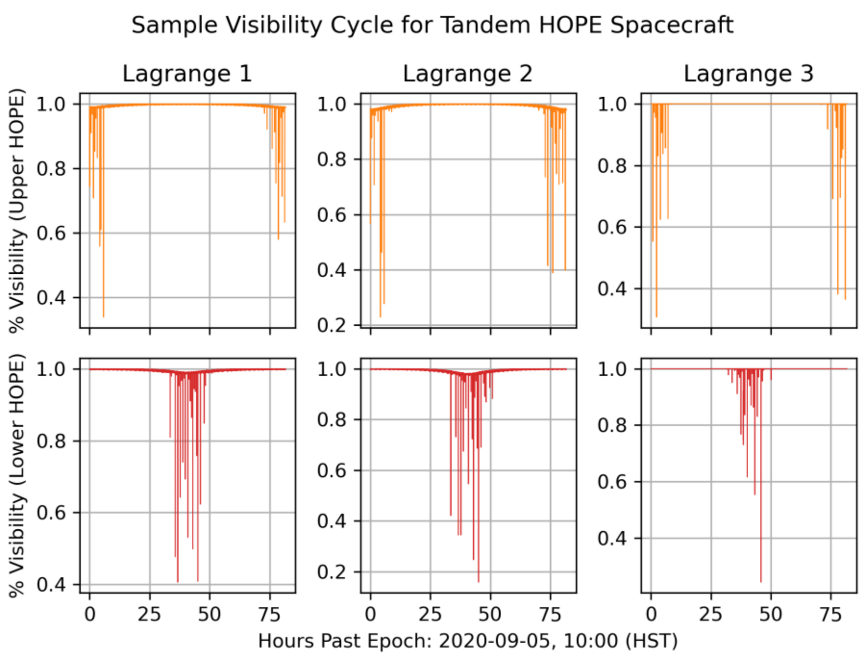

Fig. 4. HOPE Detailed Orbital Period Visibility Assessment.

Fig. 5 shows the periodic variation in coverage achieved by two appropriately-phased HOPE spacecraft. The simulation was run for a full lunar period enabling both the effects associated with the HOPE orbit geometry, including their orbit period, and the effects of moon phase to be observed. While additional effects associated with seasonal variation on an annual basis are not captured in this plot, it is notable that the autumnal equinox of 2020 occurs on September 22nd, 7 days after the epoch of 15 September 2020.

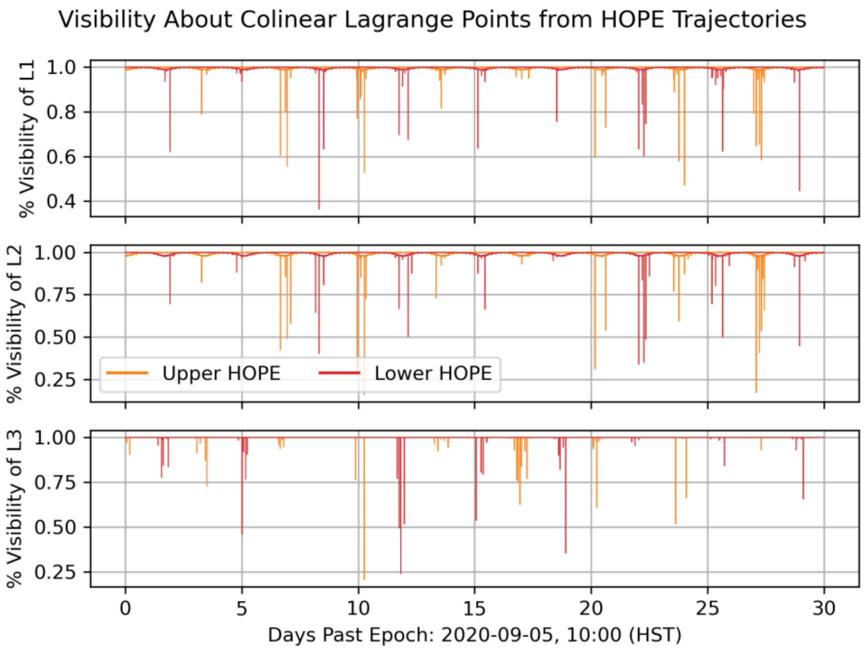

Fig. 5. HOPE Lunar Cycle Visibility Assessment.

Fig. 6 illustrates the maximum achieved coverage as a function of time, and illustrates how the conceived solution achieves persistent, near 100% coverage of the strategic locations in the cislunar regime using only two spacecraft.

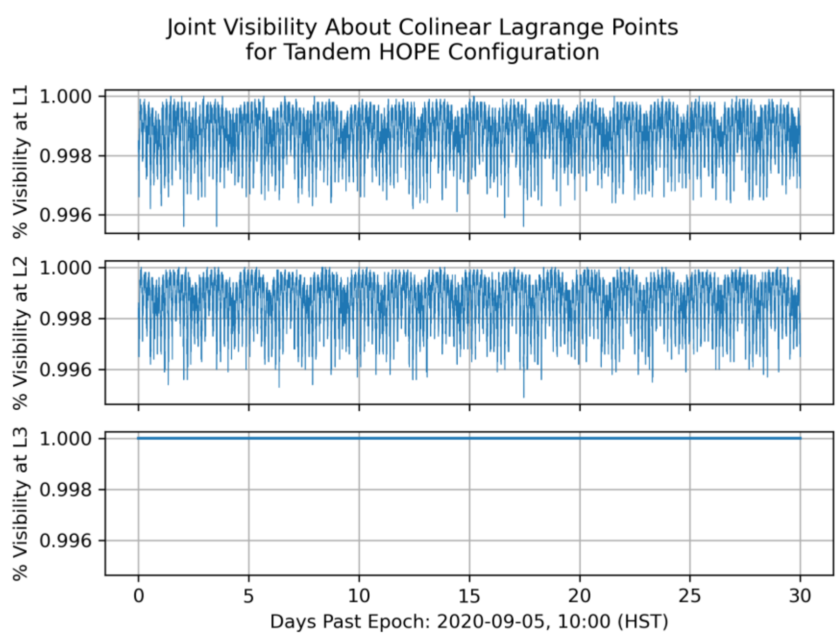

Fig. 6. Tandem HOPE Continuity of Visibility.

A brief consideration of the fourth and fifth (equilateral) Lagrange points yields results not dissimilar to the third libration point above. Fig. 7 shows the added loci of interest.

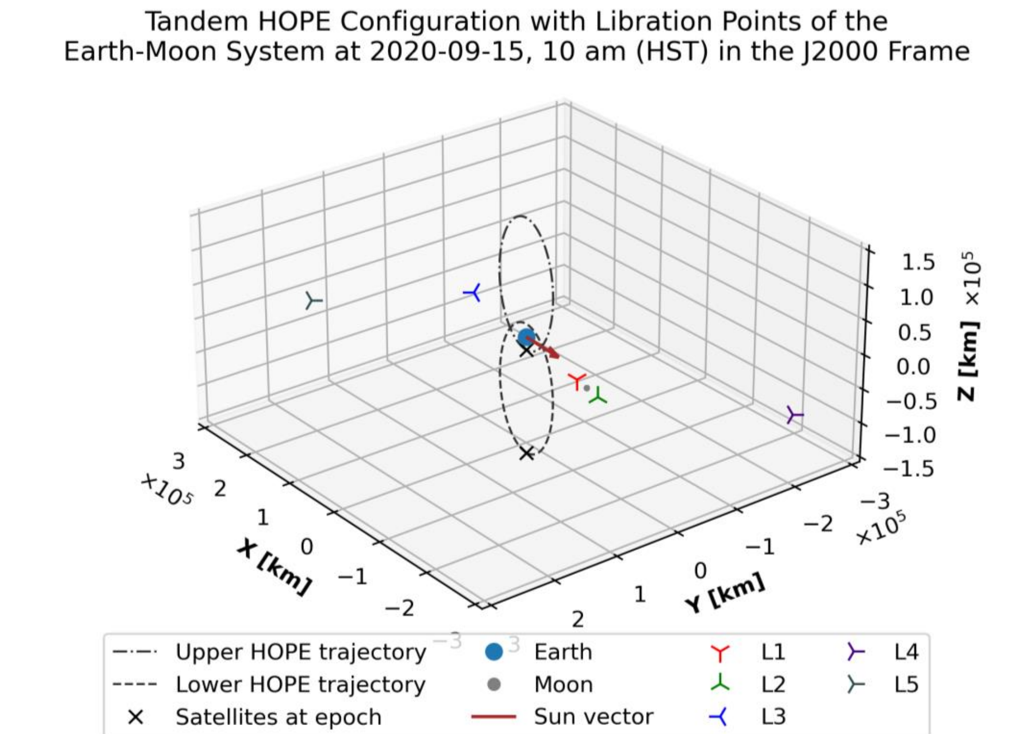

Fig. 7. Orbital Map with all Lagrange Points.

Given the fixed orientation between the moon and the equilateral libration points, lunar occlusion is not of concern. Rather, visibility metrics are driven by solar exclusion. Fig. 8 shows the favorable characteristics the tandem HOPE configuration achieves, where the joint visibility assessment showing total coverage has been overlaid in blue.

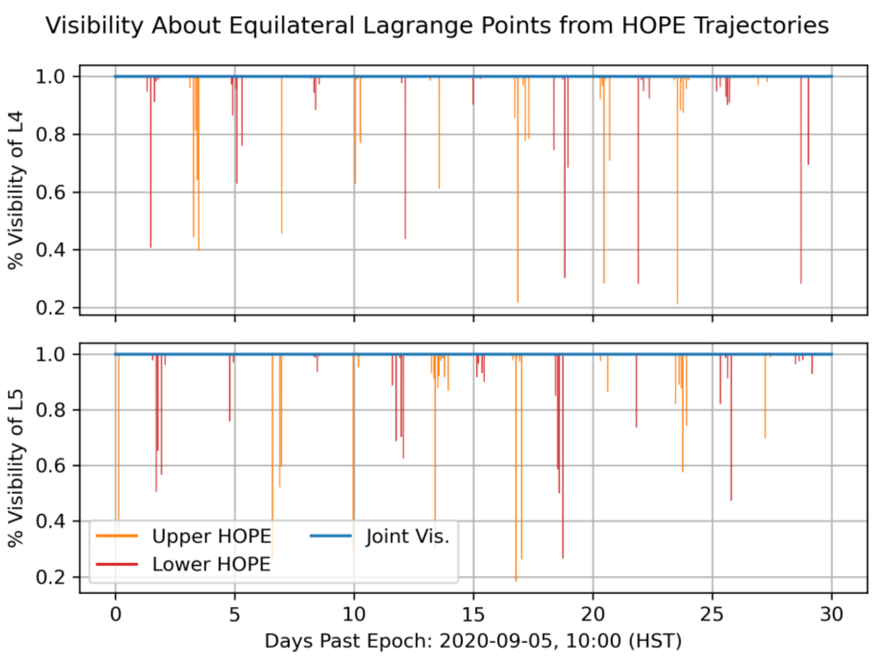

Fig. 8. Tandem HOPE Coverage of Equilateral Points.

In contrast to the above, brief consideration may be given to the observability offered from more conventional orbits. LEO, a popular regime to place a spaceborne sensor, purports to offer a cost-effective solution to mitigating the visibility degradations associated with Earth's atmosphere. Similarly, a GEO trajectory might be considered a natural station from which to monitor cislunar activities. However, even if the challenges of lower geometric diversity were overcome, a preliminary analysis of the occlusion and exclusion considerations alone, seen in Fig. 9, offers no such recommendation that a small constellation of spacecraft placed there could mitigate what would surely be a concerning obscurity.

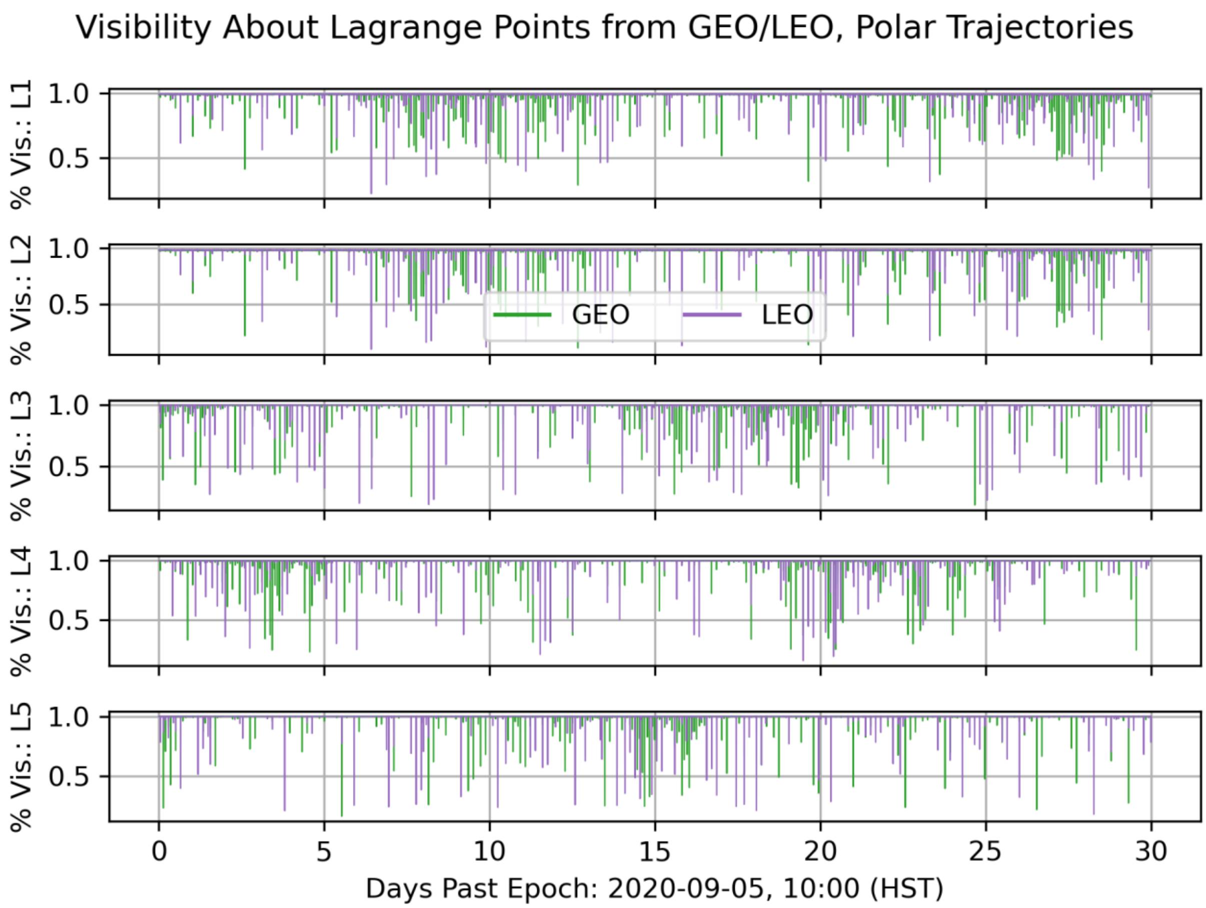

Fig. 9. Lagrange Point Visibility From Lower Orbits.

3.2 Hybrid Architectures Utilizing Ground-Based and Spaceborne Sensors

In general, ground-based sensors are easier to design, construct, deploy, and maintain than are spaceborne sensors. Spaceborne sensors have substantial advantages in sightlines and access to greater physical volumes, and corresponding challenges associated with reaching the remote locations where they are deployed and surviving the harsher environments there. The issue of balancing between ground-based and spaceborne systems will be addressed via the development of a simple cost model. This model will account for the cost of fielding a Theoretical First Unit (TFU) hardware element for both a prototypical ground-based unit and a prototypical spaceborne unit and will include as cost elements the costs to design, build, test, and deploy.

The simple cost model used here breaks these cost elements down into components. While any given elemental cost breakdown is fraught with some unavoidable uncertainty, cost ratios between different systems may show the virtue of countervailing erroneous assumptions and estimations, and the general fact of a spaceborne sensor's being multiple times as expensive as a ground-based sensor is utterly unsurprising. As such, the assessed costs of both systems are provided. One is the cost of a commercially-produced ground-based sensor unit; the other the cost of a commercially-produced spaceborne sensor. While it is generally known that government-produced large spaceborne sensors are extremely capable, they are also typically both extremely expensive and hard to cost accurately. The Hubble Space Telescope and James Webb Space Telescope (JWST) both are assessed to have had their actual costs decuple between original design and launch date, and it is further not unreasonable to assess the lifetime cost of the Hubble Telescope as having been only half-spent at launch. It is likely that the estimated $30B committed on Hubble and JSWT alone to date represents more than the total amount of funding spent by all involved parties in commercial SSA since the inception of the field.

However, costing assessments from commercial space operators provide some grounding for belief that commercial organizations can create and operate systems that are far cheaper (if far less exquisite) than can government [5]. As such, this paper will consider just hybrid architectures incorporating only the lower cost estimates associated with commercially-produced sensors. The simple initial cost model used showed a TFU cost for a single commercial-grade hosted payload of $4.26M, and a TFU for a ground sensor as $413K. The approximate order of magnitude difference in cost is not unreasonable. Although it is likely that both of these costs represent a floor rather than a most-likely cost estimate, some comparison between the two may still be instructive, and insights derived from relative comparison may scale with higher absolute costs.

The additional costs associated with a spaceborne system would be the launch costs and the bus costs. Launch costs are assumed as at minimum $3M, considering a rideshare with other payloads [6-7]. Bus costs are challenging to estimate, although we may assume that a payload calculated to operate in the HOPE environment will be on the order of 100-300 kg, meaning it will be smaller than most very large commercial buses and larger than many microsatellite buses. However, if we can assume that the bus will cost approximately $3M to purchase, we may use this as another floor. Accordingly, the TFU cost (before deployment) can be assumed to be under half of the total fielding costs.

Of the total costs to produce a spaceborne system Theoretical First Unit, or STFU, around 56.5% are estimated to apply for materials, with around 34.2% going to initial development and lab testing, and the remaining 9.3% going to facilities and acceptance testing. Using the 34.2% figure as a proxy for assembly, we may assess a learning curve, which somewhat reduces the cost for a number of spaceborne systems exceeding unity.

The table below shows costs, in the form of multiples of STFU, for a *total* of units built. Parts costs are assumed to be the same for each unit.

Table 1. Costs for fleets of spaceborne systems with learning curve effects.

Units built	Fraction: Dev/lab tests	Fraction: flight testing	Fraction: Parts	Sum costs (in STFU)
1	34.2% TFU	9.3% TFU	56.5	1.00
2	54.72	16.74	113	1.8446
3	72.04	23.61	169.5	2.6515
4	87.55	30.13	226	3.4368

If an 80% learning curve for built units is assumed, with a 90% learning curve for flight testing time, and the foregoing analysis of the utility of HOPE trajectories in this paper supports the assessment of three spaceborne sensors (two in active HOPE trajectories, and a third as an Engineering Development Unit and/or hot spare) as the desirable fleet size, then a total built cost of 2.65 times the spaceborne sensor TFU (or STFU) cost is assessed. Added to the cost of fielding two of these units, the total price to operate a spaceborne HOPE constellation in support of a ground network is approximately 5.25 STFU. Following similar estimates, a ground-based network may require approximately 0.1 STFU cost increments to produce a ground unit, and the ground deployment costs are much lower than space deployment costs. A reasonable floor for ground deployment (including both securing a location to deploy and the actual deployment effort) would be that it is 0.2 times the cost of a ground unit, or 0.02 STFU.

In terms of performance, no ground-based sensor can buy down a solar exclusion fully. (Note: extremely advanced technologies, such as fast-framing sensors, are ignored for the purposes of this paper.) Therefore, a very basic ground network should likely consist of a few tens of sensors. Sites would ideally be spread not more than 30 degrees of longitude apart, and a site north of the equator would ideally be matched with a twin to the south. This suggests a desirable number of sites as approximately 24. However, each site should be furnished with multiple sensors, so as to afford redundancy in operations and the ability to collect on multiple targets simultaneously as well as on a single target from multiple apertures (note that sensor field of view and the orbital spread of observed RSOs govern whether these are feasible; generally they may be expected to occur). It is not unreasonable to expect 4-5 sensors per site to be present, leading to a network size of approximately 100-125 sensors. If a ground network consists of a total of 100 sensors, then the entire network (including learning curve effects for building) would cost 22.7 times the cost of a ground unit (or 2.27 STFU) to build, plus 2 STFU to deploy.

Thus a spaceborne arm of a hybrid architecture is estimated to cost 5.25 STFU, while a reasonably-sized ground arm is estimated to cost 4.27 STFU. To a reasonable approximation, a small space segment is as costly as a widely-spread, built-out ground segment. There are many factors complicating this assessment, however: not least is the fact that a space segment would require the expenditure of all capital before the first dollar of revenue arrived, where a ground network would not necessarily face this problem. Additionally, the numbers used here are first-principles and simplified estimates, which do not allow for a great many complicating factors.

3.3 Commonality Among Ground-based and Spaceborne Sensors

The consideration most able to affect the lifecycle costs of a hybrid ground-based and spaceborne sensor architecture is commonality among hardware and software. For the present, commonality analysis will only be applied to the case of commonality between commercial-grade ground sensors and commercial-grade space systems.

Commonality analysis can be conducted by assessing the numbers of components that may be made common between ground systems and spaceborne systems. Broadly, eight subsystems make up a sensor assembly:

Power
Propulsion/Stationkeeping
Command and Control Processing
Data Transfer/Communications
Environmental Management
Structure
Pointing/Mechanisms
Detection Train (Optics, Sensor, and Sensor Data Processor)

Some of these eight subsystems take different forms between space and ground (e.g., a spaceborne sensor must undertake thermal management and radiation protection to survive its environment, while a ground sensor must handle weather effects such as wind and humidity). But any subsystems which are common could reduce the overall lifecycle costs of the architecture due to reduced development costs, but would in turn require some added cost in the form of more expensive components (consider that a design utilizing components common to space and ground systems would of necessity use parts overdesigned for ground factors, but adding risk to spaceborne performance).

A very simple commonality model was applied, assessing each of the eight subsystems for the potential for common parts, and then estimating the percentage of commonality in hardware and software that could be applied. The cost savings in eliminated Non-Recurring Engineering (the development and lab testing) costs were estimated by calculating the fraction of work that would not be needed if space-rated components were used on ground systems, and the added costs were assessed by estimating the additional premiums needed in parts costs. This analysis resulted in an estimated savings-to-cost ratio, as seen in Table 2. Note that this simple model does not scale with the ground network size, and thus serves only to identify subsystems with a viable potential for commonality, not fully to list validated trades for commonality. Savings/cost ratios of less than unity indicate subsystems where commonality is not likely beneficial; higher values, particularly those above 2, indicate subsystems more likely to be beneficial if made common.

Some subsystems naturally allow no commonality; it would make little sense to operate a space-rated thermal management system on the ground, or build and fly a simple weather shelter. And the pointing and aiming problem facing a ground telescope (which is presumably always in contact with the solid reference of the ground) is different in character from that of spaceborne pointing.

Table 2. Simple commonality model.

Subsystem	Ground Sensor	Spaceborne Sensor	Est. HW Overlap %	Est. SW Overlap %		Common?	Savings (STFU)	Costs (STFU)	Savings/cost ratio
Power	External Source	Bus Interface	10	30		Y	0.0057	0.0061	0.936
Prop/Stationkeeping	Base Platform	Bus Interface	0	0					
Command/Control	COTS	Rad-hard	50	70		Y	0.0069	0.0025	2.808
Data Xfer/Comms	Fiber or Sat Relay	Sat Relay	90	100		Y	0.0082	0.0018	4.446
Env. Mgmt	Weather Shed	Thermal Mgmt	0	0					
Structure	Tube + Mount	Tube, Mount, Shielding	50	0		Y	0.0015	0.0013	1.170
Pointing / Mechs	Swivel Mount	Shutter and ACS	0	0					
Detection Train	COTS	Rad-hard	50	30		Y	0.0098	0.0052	1.872

Overall, there are five candidate subsystems for common development: power systems, CDH, Communications, Structure, and Detection Train (e.g., the main sensor payload itself). The rough estimate of costs and benefits for commonality indicates that two subsystems (power and structure) are assessed to offer benefits less than or not substantially more than the costs of making them common, but three (the command/control, data transfer/communications, and detection train subsystems) show the chance of savings. While the detection train offers an apparently even trade, the command/control processing may more viably be made common, and the data transfer/communications subsystem appears potentially more appealing. In practical terms, this trade would entail placing a satellite-communications system (such as Iridium link) on every ground unit, and allows that the learning and parts chain benefits of doing so for a ground network may outweigh the costs of learning to use such a subsystem only for a spaceborne arm.

Further analysis into the practical implications and aspects of fielding near-spacerated optical units across a wide ground network is recommended, to make a complete assessment of the potential value of commonality in subsystems that make up the units of a hybrid sensor network.

4. CONCLUSIONS

This paper assessed the potential for avoiding occlusions and exclusions of key elements of the cislunar volume by operating a hybrid sensor network consisting of approximately 100 ground-based sensors and 2 active spaceborne sensors in HOPE trajectories. If such a sensor architecture were to be constructed, the ground arm would cost (to first order) the same amount as the spaceborne arm, and the use of component commonality in hardware and software would be recommended for the detection train, command and control processing, and data transfer/communications subsystems, in that order.

A deeper assessment of the potential benefits of system commonality, including a detailed review of costs (allowing for lifecycle factors such as length of effective operations and annual maintenance) is a desirable next step, and analysis of uncertainty in the effects of attempted commonality ought to be included as well. Also useful would be the development of a deeper model of commonality, including one which embraces the modeling of portfolios of common systems across various configurations of ground and spaceborne sensors in loci other than those considered here (such as ground-mobile systems and LEO orbiters).

However, the general viability and utility of HOPE orbits for near-complete overwatch of the cislunar regime, with very high persistence, has been indicated by this work, and the relative feasibility of hybrid sensor architectures including both ground and spaceborne elements has been reviewed. As long as interest in cislunar or trans-GEO space operations remains high, it is likely that an SSA sensor network to watch such activity can be conceived.

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