Dynamic Orbital Slingshot for Rendezvous with Interstellar Objects

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1. NIAC Phase I Key Finding

The solar sail "statite" concept presents a potential means to study interstellar objects (ISOs). A new class of asteroids and comets, ISOs offer a unique scientific opportunity to answer fundamental scientific questions about the origin of solar system volatiles, the compositions of exo-solar systems, and the transfer rates of material between solar systems. Unfortunately, they are also challenging to study due to their high excess energies and the short lead time offered by present detection infrastructure. By using its solar sail to "hover" in place, a statite is able to await the discovery of an ISO and, when called upon, convert the enormous potential energy of its stationary state into the velocity necessary to rendezvous with the targeted comet or asteroid. The investigation completed in Phase I focused on establishing the viability of the proposed mission concept. To do so, optimal trajectories to the two known ISOs were demonstrated and the relationship between statite placement and the resulting trajectory was explored. Post-launch trajectories from the Earth to strategic statite states were also shown to be feasible. Concurrently with these efforts, a thorough review of published ISO population estimates was conducted and preliminary steps towards creating a database of synthetic ISO ephemerides were completed. If renewed for a Phase II, this will be used to characterize the capabilities of the statite concept. The key findings of the Phase I study are:

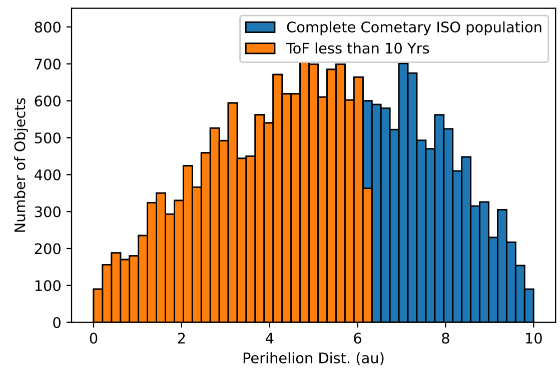

Figure 1 Perihelion distance distribution of estimated population of Pan-STARRS detectable cometary ISOs (Blue) and those accessible using the statite concept with a time of flight under 10 years (Orange) [1]

- **Finding 1:** Multiple studies support a steady state ISO population of thousands of objects greater than 200 meters in size within the solar system. In models by Hands and Dehnen, the median semimajor axis distance of their ISOs is 52.2 AU. The vast majority of ISOs in our solar system are likely asteroidal objects like 1I/'Oumuamua, and a minority of them are likely cometary like 2I/Borisov. While most of these objects are probably located in the outer solar system (e.g., $>$ 50 AU [2]) where they are unlikely to be detected, dozens may potentially be located within 6 AU and thus in range for detection and interception during the next decade. Even encountering one ISO with a spacecraft flyby would provide an unprecedented wealth of knowledge of other star systems.
- **Finding 2:** Simulations show that the forthcoming Large Synoptic Survey Telescope (LSST) will significantly increase the rate at which we discover ISOs. This will make planning missions both more feasible and pertinent.
- **Finding 3:** Rendezvous trajectories to both of the known ISOs would have been possible using the statite mission concept. Earth-to-statite trajectories were likewise shown to be practicable.
- **Finding 4:** The suitability of specific ISO targets varies. Objects with a higher characteristic energy (i.e., the energy in excess of that which is required for a parabolic escape trajectory for a given perihelion distance) are more difficult to reach, but further study using either synthetic or actual ISO data is required to fully define this relationship. An approximate representation of the portion of the ISO cometary population detectable by Pan-STARRS and reachable in under 10 years may be found in Fig. 1.
- **Finding 5:** Five ultrathin and ultralight materials have been identified as candidates for achieving full statite performance, with exceptional measured or theorized reflectances and mechanical robustness. In addition, they each show promise for reliable large scale fabrication up to thousands of square meters in the next 10-15 years.

2. Phase I Report

2.1. Summary of the NIAC Phase I Concept

The Grand Challenge of Visiting Interstellar Objects: The study of asteroids and comets has revealed a treasure trove of information about the formation and history of our solar system. In 2017, the first known interstellar object (ISO) to pass through our solar system – the asteroid ‘Oumuamua – was discovered [3] and more recently, in August 2019, a second object was detected [4] which flew by the Sun in December 2019. The existence of these ISOs offers us a great scientific opportunity to develop a detailed understanding of the formation and history of other star systems. Studying ISOs up close will be critical to answering fundamental scientific questions related to the origin, bulk composition and structure of other solar systems. However, due to their high characteristic energies and the relatively short lead time offered by present detection technology, this may be extremely difficult with current satellite propulsion systems. In this Phase I study, a Dynamic Orbital Slingshot concept was proposed for a rapid flyby or rendezvous mission to an ISO (i.e., interstellar asteroids and comets). To goal would be achieved using a statite [5]: an artificial satellite that employs a solar sail to continuously modify its orbit allowing it to hover in place. In essence, the solar sail spacecraft would be stationary in the heliocentric frame. From this state, it could wait until a suitable ISO is detected and then enter either a flyby or a rendezvous trajectory by reorienting its solar sail. The investigation of the feasibility of the use of statites for achieving a fast response capability to newly detected ISO was at the center of the innovation of this Phase I study.

2.1.1. Background

Several authors have already considered how missions to ISOs could be accomplished. Styled after NASA’s Deep Impact mission, Seligman and Laughlin considered a mission to ’Oumuamua which would complete a spectroscopic analysis of a debris plume generated by colliding an impactor vehicle with the ISO. Such a mission would have been more achievable with present technology, for, unlike a rendezvous mission, it would not be necessary to match the velocity of the asteroid. It would, however, have required a spacecraft to have been built and ready for launch upon the early detection of the ISO [6]. In response to this, Hibberd, Hein, and Eubanks identified trajectories that used a series of gravity assists to reach ’Oumuamua before 2050 from an assumed launch date in the early 2030s, thus allowing for sufficient time to construct the spacecraft [7].

Neither of these mission concepts are ideal. As a flyby and impactor mission, the former would not enable the extended study of the geology and structure of the body. Meanwhile the latter would be a lengthy mission that depends on the availability of appropriate gravity assists. To fill the technological gap necessary to rapidly respond to new ISOs and achieve rendezvous, this study proposed the use of a stationary satellite, otherwise known as a statite [5]. A statite is an artificial satellite that employs a solar sail to directly counter the gravitational attraction of a central body – in this case, the Sun – thus allowing it to hover in place. From this stationary state, the statite is able to lie in wait of a target ISO. Then, once a target is identified, the spacecraft converts the enormous potential energy of its initial, motionless state into the substantial ΔV necessary to complete a mission to an ISO.

The complete mission concept is to have a constellation of statites where: 1) each spacecraft enters into a stationary state, which it can hold indefinitely, awaiting a potential ISO; 2) once an ISO is detected, a rendezvous trajectory is calculated; 3) a single statite reorients its solar sail to enter into a controlled freefall towards the Sun; 4) the spacecraft adjusts its trajectory to rendezvous with the ISO; and 5) onboard sensors make critical scientific measurements of the asteroid or comet.

2.1.2. Initial Concept Calculations

Solar sails, which reflect light to generate a propulsive force, are not a new concept and have been studied extensively [5, 8–15]. Many of these have investigated of the orbital dynamics of solar sail spacecraft and several types of stable orbits have been discovered. These include terminator orbits [13], quasi-terminator

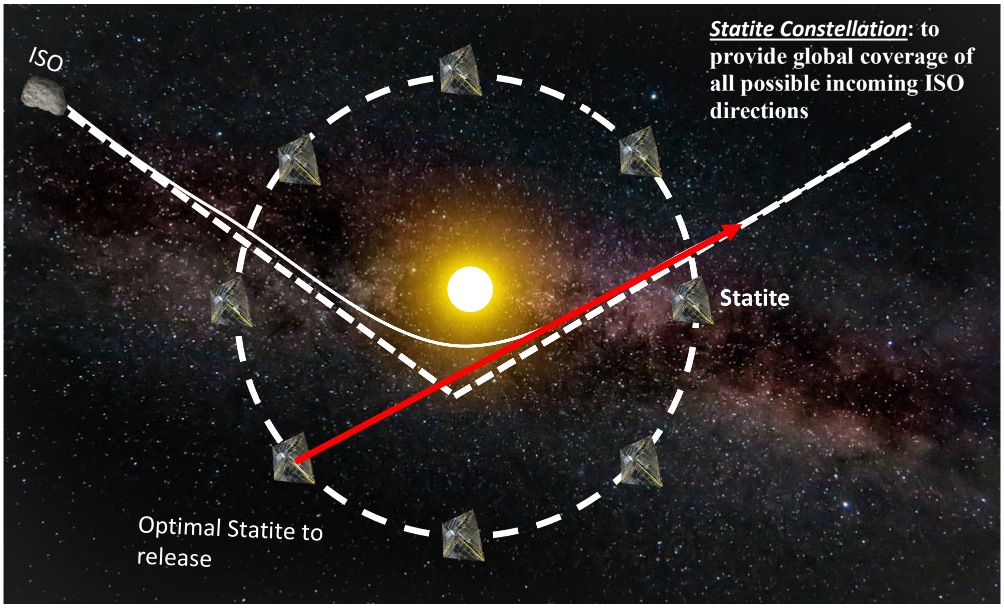

Figure 2 The mission concept: Using a constellation of Statites for global coverage (although a mission using a single statite is possible)

orbits, heliotropic orbits [8,9], and Delta-V assisted periodic orbits [14]. However, the central technological innovation considered in Phase I is not an orbit at all, but rather the use of this propulsion technology to directly counter the gravitational acceleration of the Sun.

The fundamental idea that allows statites to work is that both the gravitational force of the Sun and the propulsive force from the solar sail vary as $1/R^2$. Therefore, a statite's ability to neutralize the attraction of the Sun is independent of the distance of the spacecraft to the Sun; it is able to hover anywhere. The key parameter for achieving statite-level performance is the area-to-mass ratio, and the critical value is determined by balancing gravitational attraction and light pressure repulsion using the following [11]:

$$F = \frac{GM_{\text{sun}}m}{R^2} = 2\frac{AL}{4\pi R^2 C} \tag{1}$$

where M_{sun} is the mass of the Sun, A is the area of the sail, and L is the total light flux from the Sun at $R = 1$ (in units of AU=1.5×10^{11} m), which is $L \approx 1400\,\mathrm{W\,m^{-2}}$. Assuming an ideal sail with only specular reflections, the solar sail reflection geometry is shown in Figure 3. The mass-to-area ratio is then given by

$$\frac{m}{A} = \frac{L}{2\pi CGM_{\text{sun}}m} \tag{2}$$

Using this equation, the critical mass-to-area ratio [5, 8–11] is $1.54\,\mathrm{g\,m^{-2}}$ and the area-to-mass ratio is $0.65\,\mathrm{m^2\,g^{-1}}$. To achieve statite-level performance, the combination of payload and solar sail mass m must meet these specifications. In current advanced solar sail designs, aluminized temperature resistant materials such as CP-1 reach ratios as low as $5\,\mathrm{g\,m^{-2}}$ at a thickness of $2.5\,\mathrm{\mu m}$, but no complete solar sail spacecraft has come close to the desired statite mass-to-area ratio. It may be possible to address this issue in the future by using ultrathin materials that are the subject of ongoing research. This will be discussed in greater detail in Section 2.2.2.

2.2. Key Progress to Date

2.2.1. ISO Population

Interest in characterizing the population of interstellar visitors to the Solar System predates the discovery of 'Oumuamua. In 2017, Engelhardt et al. derived 90% confidence limits for the spatial number density of ISOs about 1 km, by conducting a simulation of Pan-STARRS in order to detect a population of 'synthetic' ISOs. Figure 4 shows the distributions of orbital elements of the ISO trajectories detected in this simulation. The upper values were 1.4×10^{-4} au^{-3} for "active" objects, which display comet-like qualities, and 2.4×10^{-2} au^{-3} for "inactive" objects, or those which are asteroidal in nature [16]. Following the discovery of 1I/'Oumuamua and 2I/Borisov, other groups recalculated ISO population densities. Using the single detection of 'Oumuamua by Pan-STARRS during its 3.5 year search, Do et al. determined a mean density of interstellar asteroids with sizes greater than or equal to 100 m of 0.2 au [17] that roughly corresponds to the that suggested by Engelhardt et al.

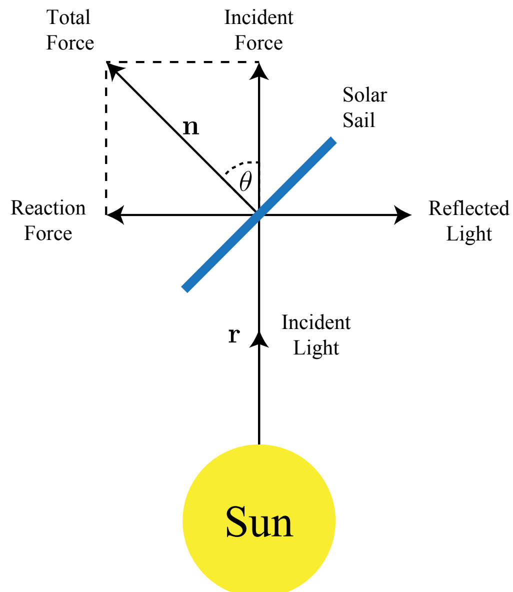

Figure 3 Ideal Solar Sail Reflection Geometry

Others have worked to determine the flux of ISOs in our Solar System. By simulating interactions of ISOs with the Sun-Jupiter system using the velocity distribution of nearby stars and Do et al's number density, Hands and Dehnen inferred an ISO volume capture rate of 0.051 au^3 yr^{-1}. They also estimated a steady state population of captured ISOs of approximately 10^2 comets and 10^5 'Oumuamua-like asteroids. However, of this steady-state population, they estimated that only 0.033% of objects are within 6 au at any given time [2].

Understanding the expected detection frequency will also be important to establishing the impact of the proposed research. Seligman and Laughlin performed a simulation of Pan-STARRS and LSST in order to calculate an approximate value. Using Monte Carlo methods, they estimated an ISO detection rate of roughly one-per-year with the LSST, which was approximately 70 times more frequent than Pan-STARRS detections. They found that Pan-STARRS is more likely to detect objects in spring, while LSST showed little variability across seasons [6]. These studies suggest that there is a significant population of ISOs in our solar system, and that we will continue to detect more objects like 1I/'Oumuamua and 2I/Borisov in the near future, especially with the start of LSST operations.

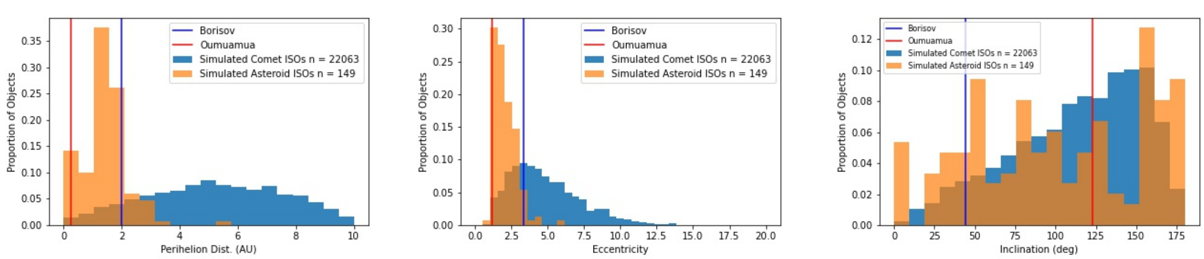

Figure 4 Detected cometary and asteroidal ISO (min. diameter 0.527 km) perihelion distance, eccentricity, and inclination distributions from Engelhardt et al. Pan-STARRS simulation

2.2.2. Materials

To achieve the fully stationary state of a true statite, an ideal, flat solar sail which perfectly reflects all incident light must have an areal mass of at most $1.54\,\mathrm{g\,m^{-2}}$. However, a spacecraft is more than just a sail. To offset the mass of scientific instrumentation and the rest of the satellite bus, sail materials must therefore have an areal mass that is smaller than this critical value. Additionally, real sails are not ideal. They crease and wrinkle when folded and unfolded, billow under the force of solar pressure, and do not reflect all light. As a result, the actual force generated by solar radiation pressure is less than that estimated for an ideal sail, as does the desired lightness number, which becomes $1\,\mathrm{g\,m^{-2}}$ or much less. Standard solar sails today use a mechanically robust base layer of a polyimide or mylar a few microns thick. It is then coated in 10-20 nanometers of aluminum on one side for reflectance and chromium on the other side for thermal radiation. NASA's NEA Scout, a solar sail planned for launch in 2021, will feature an $86\,\mathrm{m^2}$ sail made from colorless polyimide 1 (CP-1), which has a mass of about $5\,\mathrm{g\,m^{-2}}$ at $2.5\,\mathrm{\mu m}$ thick. With payload included, however, the whole spacecraft is 14 kg and has a lightness number of $163\,\mathrm{g\,m^{-2}}$ – 100 times more massive than allowable for a statite [18].

The necessary performance may be achieved using materials under development that exhibit both mechanical robustness and acceptable reflectance at nanometer thicknesses. Since it was first isolated in 2004, carbon's atom-thick allotrope graphene has been the subject of extensive research. These efforts have resulted in the discovery and production of 2D films, materials only a few atomic layers thick. By combining desirable optical and structural properties with extremely low areal densities, graphene and other 2D materials like Transition Metal Dichalcogenides (TMDCs), silicon nitride and hexagonal boron polymorphs, and other metamaterials engineered as photonic crystals show promise for radiative propulsion.

Researchers of the Starshot Lightsail project, which aims to design an ultralight spacecraft to send to Proxima Centauri B, have proposed several variants of molybdenum disulfide (MoS_2) and crystalline silicon (c-Si) as optimal candidate materials for their sail. These materials use refractive index contrast by alternating monolayers with aerogels to create photonic band gaps which cause near unity reflectances in the near-infrared spectral range, which contains a significant portion of the Sun's radiation [19–21]. They can also be engineered as single-layer photonic crystals with nanoscale holes or pillars that produce similarly desirable reflectance values with even less mass. To increase its emissivity for thermal management, a layer of SiO_2 may be added to the back of the sail.

Hexagonal boron and its polymorphs are another promising material candidate. Gupta et al. have theorized that one of these forms may be able to produce 99% broadband reflectivity over essentially all the Sun's radiation spectrum with a thickness of just 40 nm, or a mere 100 layers [22]. This material, while meeting the constraints of a true statite's lightness number, has not been fabricated, and its mechanical properties are thus unknown. Silicon nitride, on the other hand, can easily be produced at tens of nanometers with strong tensile strength and broadband reflectivity [23]. Research continues into producing photonic crystals of silicon nitride with even higher reflectances using novel nanoengineering techniques.

An entirely different option for a statite sail material comes in the form of aerographite. A porous solid with a density of $180\,\mathrm{g\,m^{-3}}$ made of webbed carbon nanotubes, this substance exhibits high tensile strength and optical absorption at 1 mm thickness or less [24]. With near-unity broadband absorptivity, incident photons provide half the solar pressure as reflected ones would, but still enough force for full statite performance.

Manufacturing and deployment pose additional challenges to 2D solar sails. To create a usable product, chemically pure sheets of hundreds or thousands of square meters must be produced, as well as the necessary sail stowing and deployment mechanisms. Current manufacturing methods such as chemical vapor deposition have produced 2D thin films in flakes as large as millimeters in diameter for some materials, but most have only reached micron scale or remain entirely theoretical. Besides further developments for the synthesis and fabrication of 2D materials, these issues may be addressed by stitching smaller film sections

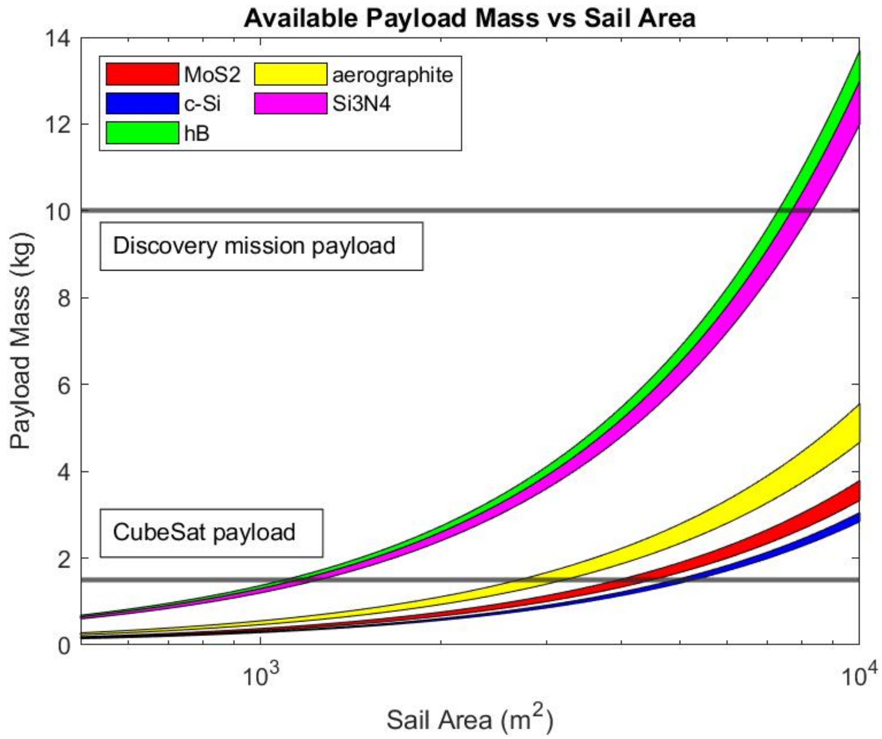

Figure 5 Payload vs. Area for Five Material Candidates

together using strong, light materials like carbon nanotubes. While gridded interstices or a substrate frame can add extra mass to the sail, the potential for new rigidity and tension in the sail could allow for less mass in the sail booms and supporting structures. Another concern is that an ultrathin sail may rip while folded due to interactions between layers governed by van der Waals forces. While no formal descriptions of solutions to this problem were found in literature, it is reasonable to consider using a slightly thicker layer of plastic as a barrier between layers during launch that can be jettisoned once the sail is deployed in space [25, 26].

Absorbance, reflectance, thickness, and density values[1] for five sail material candidates – MoS_2 photonic crystal (MoS_2), crystalline silicon photonic crystal (c-Si), hexagonal boron (hB), aerographite, and silicon nitride photonic crystal (Si_3N_4) – were used to calculate respective solar pressure and gravity forces on sails of different proposed areas. For each area, the largest possible mass of a payload such that solar pressure remained greater than gravitational force (for statite performance) was calculated and then plotted in Figure 5. The mechanical properties of each material varies as a function of its thickness, so a range of mass values are provided for each material that are contained by two bounds: a minimum payload associated with a thicker, heavier sail of greater strength and durability, and a maximum payload that results from sacrificing durability with a thinner, lighter sail, but one that could still theoretically maintain its integrity and shape. Some optical values that vary with thickness have been accounted for as well. Effective solar reflectance values have been diminished by 5% to help account for sail billowing. Note the two horizontal lines in Figure 5. These mark the payload masses of a Discovery-class mission (10kg) and a small CubeSat (1.5kg). The intersection of these lines with the colored sail material regions indicate the approximate sail area needed for each mission type.

[1] Many of the values used in this calculation are estimated based on the results for optical and mechanical properties of the materials found in multiple studies. Some values are the result of theoretical calculations and some are measured. The graph is primarily meant to show the breadth of options for statite sail materials and not to be referred to for precise values.

2.2.3. Trajectory Results

To evaluate the proposed mission concept, three questions were addressed. The first was to determine whether statite-performance solar sail spacecraft were capable of rendezvousing with the two known ISOs. To address this, optimal time of flight (ToF) and departure date rendezvous trajectories were produced using direct optimization methods. These were then compared against equivalent trajectories for spacecraft using the present state-solar electric propulsion (SEP). Next, contour plots were produced to study the impact of initial statite placement on mission performance. Finally, the feasibility of placing solar sail spacecraft into statite states throughout the Solar System was considered.

Trajectories to 'Oumuamua: The optimal time-of-flight trajectory was produced first. For this case, the starting location was left free, with only the distinctive zero initial velocity of a statite required. The starting location was found to be well within the inner solar system and the spacecraft's motion was contained within the orbital plane of 'Oumuamua. This latter point is a key advantage of a theoretical constellation of statites; without the limitation of placing spacecraft into a limited number of staging orbits, out-of-plane motion can be eliminated before a mission begins by selecting an appropriately placed statite from a sufficiently dense and widespread constellation. Having departed on August 19, 2017, the spacecraft would have arrived at the ISO on September 24, after a flight time of a mere 36 days. This trajectory is shown in Fig. 6, along with the Earth's orbit to provide context of the scale. The starting and rendezvous locations are represented by a green and red dot, respectively, with the trajectory in blue and the sail normal vector at each control point displayed in black. 'Ouamuamua's trajectory is represented as a solid red line before, or dashed red line after, the spacecraft's arrival at the ISO. The details of this trajectory, along with all others discussed in this section, may be found in Table 1.

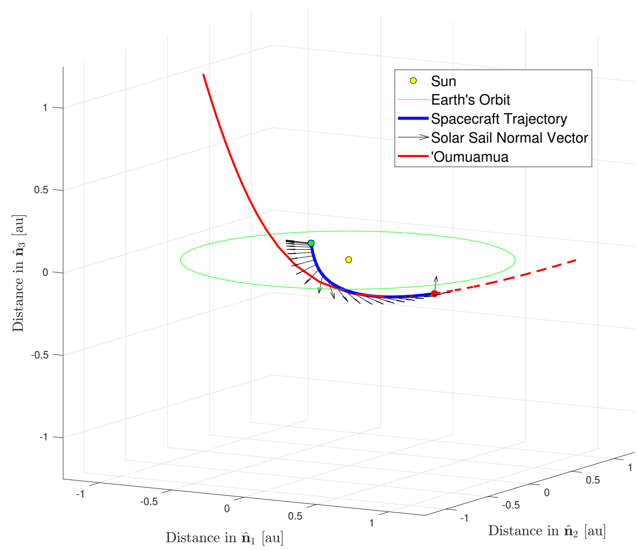

Figure 6 ToF-optimized 'Oumuamua Trajectory

'Oumuamua was discovered on October 17, 2017, having reached its perihelion a few weeks earlier on September 9, 2017 – both after the ToF-optimized trajectory's departure date [27]. The results were therefore reoptimized to find the latest possible date that the spacecraft could depart its statite station. This improved the departure date by 4 days, but at the cost of doubling the ToF to just shy of 75 days. This suggests that, for the geometry of this particular ISO's orbit, earlier detection would be necessary to achieve a rendezvous, but not dramatically so.

To compare this performance with present propulsion technology, rendezvous trajectories have been produced for a spacecraft using solar electric propulsion. These SEP trajectories were constrained to depart from Earth with $C_3 = 0$, rather than from a heliocentric statite state like the solar sail trajectories. Stationary hovering with SEP, while perhaps technically achievable, would require a prohibitive expenditure of propel-

Table 1 'Oumuamua Results Summary

Propulsion Type	Objective Function	Departure Date	Arrival Date	Time of Flight (days)
Solar Sail	Time of Flight	Aug. 19, 2017	Sept. 24, 2017	36.0411
	Departure Date	Aug. 23, 2017	Nov. 6, 2017	74.9646
Solar Electric	Time of Flight	Aug. 17, 2016	Sept. 3, 2017	381.9
	Departure Date	Aug. 18, 2016	Sept. 5, 2017	383.0

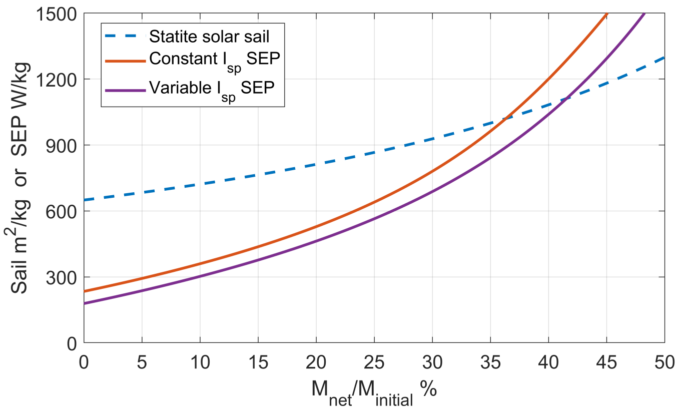

Figure 7 Higher specific area and specific power deliver higher net mass to 'Oumuamua

lant. The results, shown in Table 1, indicate that flight times would be an order of magnitude greater than those achieved by the solar sail spacecraft. Most of this increase was due to the departure date shifting one year earlier, which would necessitate far earlier detection of the ISO.

The SEP examples in Table 1 are just two instances in a broader optimization trade space, where SEP system specific power determines the available net mass. Conversely, the minimum specific power and statite specific area requirements can be determined for a given net mass fraction. Figure 7 shows the optimum sail and SEP parameters for rendezvous with 'Oumuamua, where the SEP flight time is capped at 400 days and the I_{sp} varies to an optimum. (The optimal "constant I_{sp}" changes along the shown curve, but is constant throughout each individual trajectory. The jet/input power efficiency was assumed to be 50% in lieu of a specific thruster model.) It is noteworthy that solar arrays produce approximately 450 W m^{-2} (35% efficient) at 1 au, thus the optimal SEP arrays are two-to-three orders of magnitude smaller than the optimal statite sail areas.

The effect of statite starting location on flight time was also explored. With the discovery that the optimal trajectory began in the plane of the ISO's trajectory, a mesh of starting locations in this place was created and trajectories were optimized from each. The resulting contour plot is provided as Figure 8. The trajectories with the shortest flight times start close to the Sun, with the red-dashed optimal trajectory coming into contact with the 0.2 au constraint, marked by a circle about the origin. The time-of-flight then increases with distance from the Sun. The layers are not perfect circles, however, and show some bias towards the oncoming direction of the ISO. Not shown in the contour plot are the two families of solutions: those with the perihelion constraint active and those with it inactive. All statite trajectories fall towards the Sun to gain velocity. However, if a starting location does not provide a path that aligns with the ISO's motion, the spacecraft must complete a partial revolution of the Sun. To gain the highest possible velocity, the spacecraft will complete this maneuver at the minimum solar distance permitted. This is shown in Figure 9. In the top half of this diagram, the two families of solutions smoothly transition from one to the other as the turning angle increases. In contrast, a discontinuity exists to the bottom right where the trajectories either head directly to the ISO or are forced to complete an approximately 270 deg revolution of the Sun. This may explain the non-circular shape of the inner contour layers.

Trajectories to Borisov: Compared to 'Oumuamua, the comet Borisov has a higher perihelion and excess velocity, both of which impacted the trajectory solutions. The optimal time-of-flight trajectory, shown in Fig. 10, began from a statite location some 4.7 au away from the Sun, while the equivalent trajectory for 'Oumuamua started within 0.3 au. In general, the distances traveled by spacecraft heading towards Borisov often exceeded 30 au, which in turn required long mission times. A summary of the time-of-flight and departure-date optimized trajectories may be found in Table 2. The optimal time-of-flight to Borisov was found to be 6.45 yrs. This grew to 7.26 yrs when optimized for departure date, while delaying the beginning

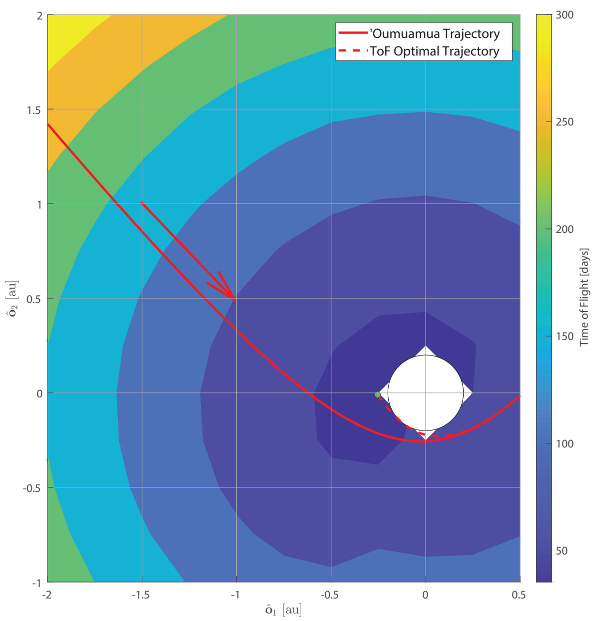

Figure 8 'Ouamuamua Time-of-Flight

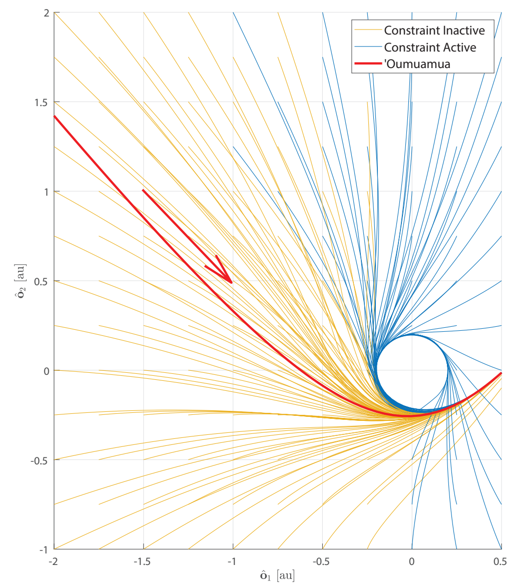

Figure 9 'Oumuamua Trajectories with Perihelion Constraint Status

of the mission by 236 d from March 17, 2014 to February 14, 2015. In comparison, the equivalent SEP trajectories were noticeably faster and departed from the Earth later.

One theory for the discrepancy in performance between the 'Oumuamua and Borisov cases was that Borisov had a much higher perihelion distance. To evaluate this theory, synthetic ephemeris data was generated to evaluate the statite's ability to rendezvous with a theoretical ISO at increasing perihelion distances and hyperbolic excess velocities. Shown in Fig. 11, perihelion distance was found to increase the ToF. It was discovered, however, that velocity v_∞, and thus the C_3 of the object, was a far greater factor.

The acceleration required to achieve rendezvous in a given flight time drive the sail specific area and EP specific power values. Figure 13 shows the optimum sail and SEP parameters for rendezvous with Borisov, with SEP flight time is capped at 700 days. The specific area curves are the same for both 'Oumuamua and Borisov because they both assume statite-level acceleration for any size payload. Further, longer flight times would allow a less demanding sail specific area for a given payload ratio. The same holds true for EP specific power. However, the initial acceleration varies with EP payload ratios due to the addition of propellant. In this case the mass of propulsion system balances the mass of propellant to minimize specific power, where higher absolute power levels entail higher system mass but lower propellant loads.

This system-level optimization provides a rich design space for ISO rendezvous architecture trade studies. In Phase II we will broaden our initial trade space to explore the effects of lower solar sail accelerations and variable time to rendezvous when comparing sails to other propulsion technologies. We have found that, for a given combination of payload ratio and specific mass or power, solar sails permit shorter times to rendezvous for one class of target (e.g. 'Oumuamua) while EP is more effective for other targets (e.g. Borisov). A statistical sampling of synthetic ISO populations will further refine this delineation.

Table 2 Borisov Results Summary

Propulsion Type	Objective Function	Departure Date	Arrival Date	Time of Flight (Years)
Solar Sail	Time of Flight	Mar. 17, 2014	Aug. 26, 2021	6.4455
	Departure Date	Feb. 14, 2015	May 17, 2022	7.2589
Solar Electric	Time of Flight	July 4, 2018	Mar. 9, 2020	1.7660
	Departure Date	Aug. 24, 2018	Jan. 24, 2024	5.4230

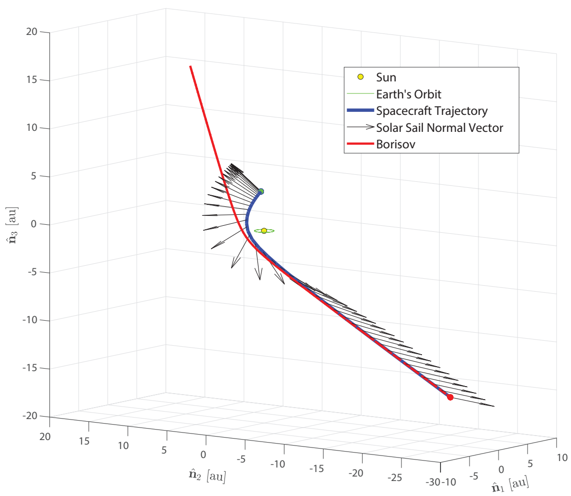

Figure 10 ToF-optimized Borisov Trajectory

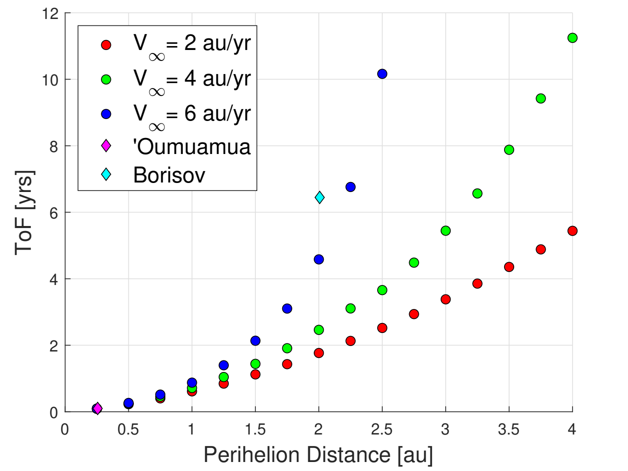

Figure 11 Time of Flight as a function of Perihelion Distance and Hyperbolic Excess Velocity

As with 'Oumuamua, a contour plot was produced for Borisov and is shown in Fig. 12. While 'Oumuamua had two families of solutions, only a single local minimum existed. In contrast, for Borisov, there were two separate local minima: one for trajectories with the perihelion constraint active and one with it inactive. The globally optimal solution, projected onto Borisov's plane of motion, is presented as a red dashed line that starts from a location that is distant from the Earth and Sun. This is representative of the constraint-inactive family of solutions. The second group of solutions are grouped about the origin and require a revolution of the Sun with a low perihelion. As shown by the black dashed trajectory, solutions in this family approach the time-of-flight optimal solution after gaining speed and completing a revolution. Between these two local minima lies a transition region of reduced optimality. Outside of these two basins, optimality becomes increasingly poor as a function of distance from the Sun, in a manner similar to that of the 'Oumuamua solutions.

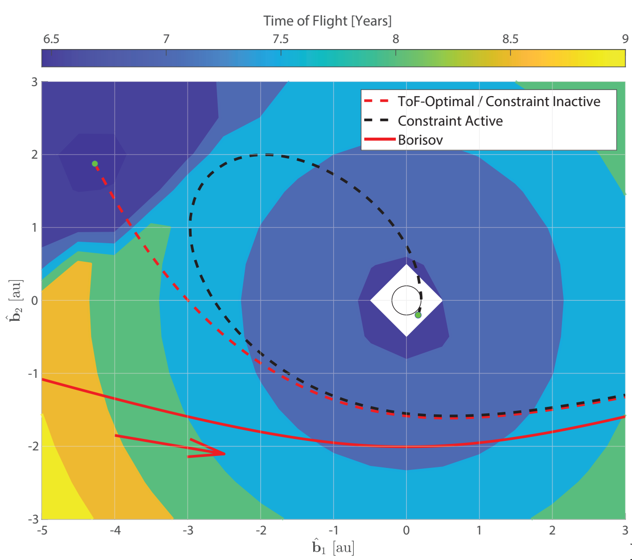

Figure 12 Borisov Time of Flight with Trajectory Overlays

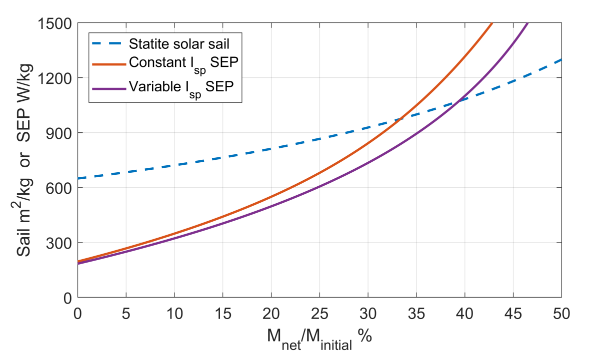

Figure 13 Minimum sail and SEP efficiencies required to deliver a given net mass to Borisov.

Earth to Statite Transfers Having established that the statite to ISO leg of the mission is feasible, the viability of sending spacecraft to these starting locations from the Earth is now considered.

By using two-body orbital mechanics, the problem environment displays both planar symmetry above and below the ecliptic and axial symmetry about the axis normal to the ecliptic at the origin. As a result of the former, the ToF to statite locations above and below the ecliptic are identical. With the added assumption that the optimal launch date from Earth is always available, the latter, axial symmetry makes the ToF to any point independent of its longitude. The contour plot in Fig. 14 therefore encompasses all potential statite locations up to 2 au from the Sun in the ecliptic and 1 au above or below the plane.

Fig. 14 shows that two local minima exist in the ToF of trajectories from Earth to statite states. In the inner solar system, there exists a family of solutions with flight times that roughly decrease with proximity to the Sun. The minimum within this family (and globally) is a ToF of 161.4 d at 0.25 au in the ecliptic. A second family exists beyond Earth's orbit with a minimum at 1.45 au in the ecliptic of 199.3 d. In both families, out-of-plane statites consistently required longer flight times to reach their station, but the ToF varied less with radial distance than in the ecliptic. This is apparent in Fig. 15, in which the out-of-plane ToF curves are flatter than those in the ecliptic.

As with Borisov trajectory solutions, solutions within the inner local minimum required a flyby of the Sun at a low perihelion, while the outer solutions did not. This is illustrated by the two example trajectories in Fig. 16. Both are shown to depart from the Earth and arrive at a point 1.1 au from the Sun in the ecliptic – the transition region between the families of solutions – but only one approaches the Sun. Note that while both shown departing from the same location, the destination of either trajectory may be rotated about the Sun by changing the launch date.

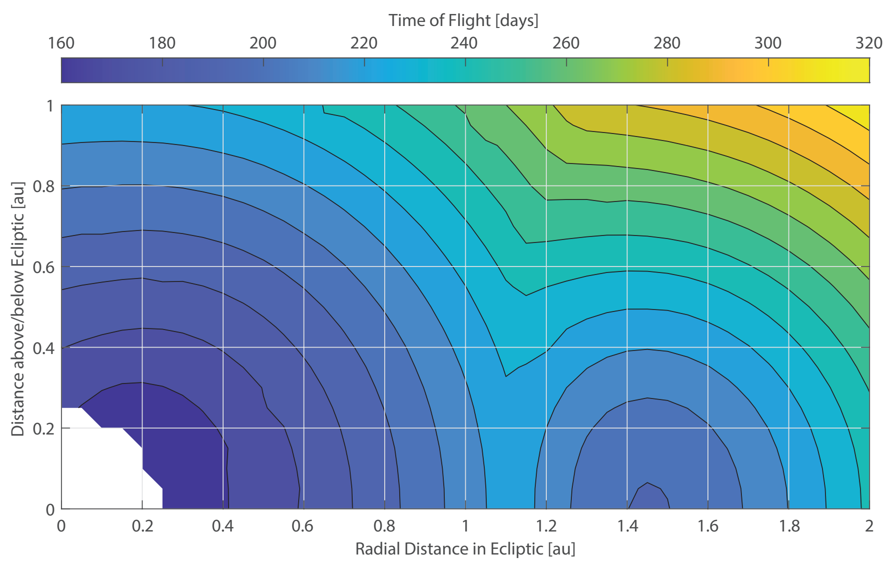

Figure 14 Earth to Statite Time-of-Flight Contour

2.3. Mission Context

Although single-statite missions are promising and possible, a constellation of statites would be superior for responding to future ISO targets. Moreover, a constellation could respond to multiple ISO events simultaneously and sample a wider distribution of these objects. Figure 2 illustrates the concept of a constellation of statites located at 1 AU and ready for deployment. When an ISO is detected, the most optimally placed statite is released. From our Phase I simulations, this statite should be able to reach the ISO in a short amount of time. As more statites are released, gaps will open in the constellation and other statites can be phased in their locations to fill these gaps. Finally, should replacement statites not be launched, the last statite in the constellation is released from a potentially sub-optimal location, but nevertheless achieves either a rendezvous or flyby with its designated ISO target.

To better understand the potential of the statite constellation concept, the flight times to the over twenty-

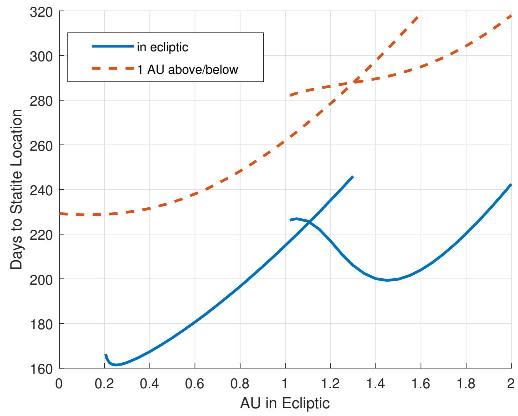

Figure 15 Earth to Statite ToF as a Function of Distance in the Ecliptic

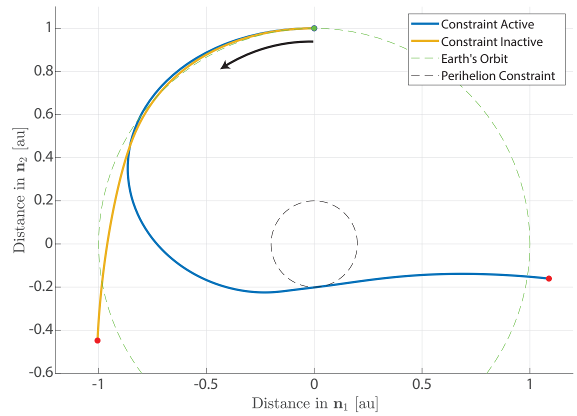

Figure 16 Earth to Statite Trajectories with and without the Perihelion Constraint

two thousand simulated objects from Engelhard et al. [16] were estimated using a multivariate polynomial function fit to the results shown in Figure 11. Approximately half of the expected comets and nearly all of the asteroids were found to be reachable within 5 years of statite release (Figure 17 left and center). By increasing the mission time to 10 years, all of the cometary ISOs up to 6 au and the entire expected asteroidal ISO population became reachable (Figures 1 and 17 right). This highlights the remarkable promise and capabilities of the statite concept.

2.4. Conclusion

Interstellar objects are a class of asteroids and comets that provide an extraordinary opportunity to learn about both our solar system and those throughout the galaxy. Due to their high characteristic energies and the difficulty of detecting them, they are also challenging to study using present propulsion technology and a traditional multi-year mission planning and execution timeline. We therefore proposed a rapid response capability enabled by statites. These spacecraft use a solar sail to directly counteract gravity. By doing so, they can hover indefinitely in a motionless state and wait for an ideal target object to be selected. Once this occurs, a single spacecraft from a larger constellation reorients itself and accelerates to a high velocity by falling towards the Sun. This allows it to establish a rendezvous trajectory to the ISO. Due to this conversion of potential to kinetic energy, this concept was dubbed a dynamic slingshot.

In this Phase I study, the ability to respond to ISOs was demonstrated using optimal rendezvous trajectories to both 'Oumuamua and Borisov. It was shown that the optimal placement for statites is within the plane of motion of a target object and that time of flight is a function of both the characteristic energy and the perihelion distance of the ISO. Placing statites into their stationary states from an Earth departure was also shown to be readily doable. To prepare for future studies, synthetic ephemerides were also collected from sources in literature. Finally, candidate sail materials were identified that may provide the necessary solar

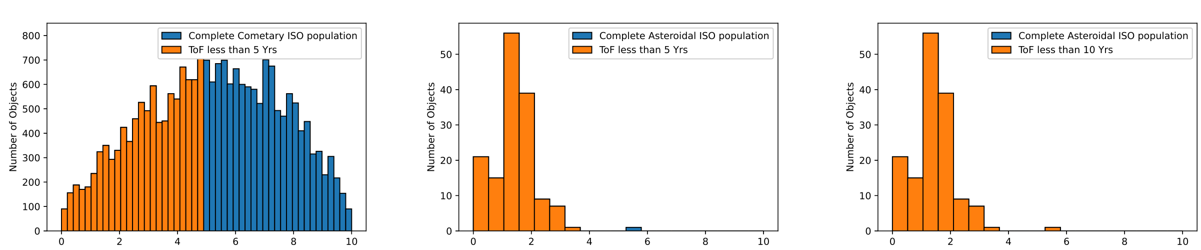

Figure 17 Expected cometary (left) and asteroidal (center, right) ISO populations and the reachable portion in under 5 years (left, center) or 10 years (right) from Engelhardt et al. Pan-STARRS simulation

sail performance to enable the statite concept in the coming two decades. Based on the combined findings of this report, this mission concept is an innovative means of solving the difficult problems involved in the study of interstellar objects.

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