Delta-V Distribution for Mission Requirements Towards an Interstellar Object

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Interstellar objects have fascinated science space since their detection in October of 2017, with the first ISO 'Oumuamua. Sub-kilometer sized asteroid-type interstellar object has been part of many different studies, ranging from its long range imaging, and estimation of its composition to a proposed mission plan towards it. Similarly in 2019 the science space has been blessed with the detection of interstellar comet Borisov, which unlike 'Oumuamua has passed further from Earth, and similarly when it was detected it was too late to launch any mission for its analysis. As there is a potential chance of detecting more interstellar objects in the near future, the development of robust missions and preparations increases. Therefore, the following paper aims to discuss the simulation approach in determining the Δv required to reach interstellar objects, and on the basis of the obtained data discuss the feasibility of reaching the simulated interstellar objects. For the simulation base a randomly generated set of $100,000$ objects has been produced, with trajectories aimed into the solar system. This pool of objects has been generated for each magnitude of ISO, in this case for velocity at Heliosphere of 'Oumuamua $26.657 km/s$ and Borisov $32.286 km/s$. Once random generation of position and velocity has been produced, ISOs have been tested to reach within $3AU$ of Earth, which has been determined as optimal, based on the initial detection range for Borisov. Throughout the propagation of ISOs, Lambert transfers are made towards it with variable time of flights, through which a set of minimum $\Delta v's$ are calculated and their distribution plotted. The distributions are plotted for the variable spacecraft position of Earth SOI, Earth-Sun L1, L2, L4, L5 and Venus and Mercury, the most beneficial of which is Earth with 7.911% reachable objects under $\Delta v = 10 km/s$. Further benefits have been gained by combining multiple spacecraft positions for Earth + L5 + L4, yielding 17.711% reachable objects, significantly increasing the probability of success. Due to this increase in number of interstellar objects reachable, the swarm based approach of small spacecraft poses the highest chance on succeeding in fulfilling missions towards the ISOs. This is because small spacecraft can not only be positioned in swarm at singular space but also distributed throughout the Solar system, allowing simultaneous launch from multiple positions, and increasing the chance of reaching the interstellar object.

I. Introduction

The interstellar objects offer the opportunity to analyze distant solar systems, learning about their origin and development, while not requiring expensive, let alone unfeasible, development of interstellar spacecraft. Rather, as these objects pass through our Solar system, they bring us miseries to be explored with them. Due to the currently limited detection pool of only two interstellar objects, it is hard to predict when another object might pass throughout the solar system. However, despite this uncertainty, their importance for scientific exploration remains. Therefore, performing analysis on different trajectories, and requirements for reaching objects on these trajectories becomes important. This is due to the potential in discovering if there is even a possibility with current propulsion and technological methods to reach these objects, or if based on the statistical data we would need a miracle to reach the interstellar object such as 'Oumuamua or Borisov. As such due to this need a simulation blackbox is developed for performing a Monte Carlo simulation for randomly generated interstellar objects to which a Lambert transfers are performed.

II. Simulation Setup

As highlighted the simulation Blackbox is developed for generation, propagation and analysis of interstellar objects. For the computing environment of choice, the MATLAB 2023b version has been utilized. This is primarily due to its fast prototyping capabilities as well as robust functions for performing spacecraft and object propagation. Within this programming environment the following assumptions and setup decisions were made.

Initially, the objects are generated with random position and velocity, as unit vectors, which are then adjusted by position magnitude of Heliosphere, and the velocity magnitudes for 'Oumuamua, $26.657 km/s$, and Borisov, $32.286 km/s$. The quantity of generated objects can be user determined, however for the purpose of this paper, a pool of 100,000 objects has been generated in order to have a large statistical backing for the analysis. Once the objects are generated, an initial velocity vector check is performed. This is in order to ensure that the randomly generated interstellar objects are propagating into the solar system, rather than out. After this preliminary adjustments, a detection checks are conducted, with the initial obtaining the orbital parameters of the ISOs, with the focus on calculating the semi-major axis of the orbit, from which a perihelion check of 4 AU is done. While this test might seem arbitrary, and the chosen variable is user adjustable, it has been applied in order to ensure that the ISOs are propagating into the inner parts of solar system, rather than out to the outer parts, where a mission would be difficult and complicated to conduct. In tandem with this check an eccentricity is analyzed to be higher than 1. Next check is for detection range of Earth which is performed for 3 AU, based on the initial detection range of Borisov.

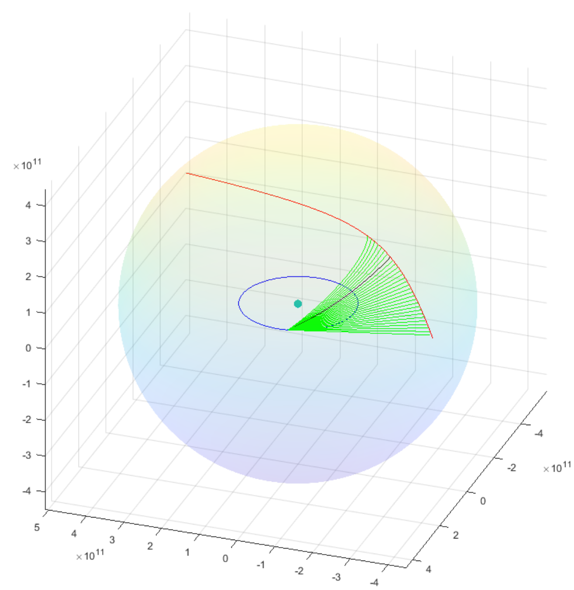

Fig. 1 Example of Singular ISO propagation through 3 AU Earth detection range with Lambert trajectories, (black) representing the minimum Delta-V case.

Once all of the ISOs have been generated and tested for detection from Earth, the determination of $\Delta v's$ is performed. For this it is assumed that Earth is stationary and that spacecraft launch without the delay, immediately when the ISOs are detected. Based on this fixed assumption, a set of time of flights ranging from 5 days till 8 years is performed with Lambert transfers, from which the $\Delta v's$ are calculated. Once each Δv is calculated then the minimum for Each TOF, for each of the 100,000 ISOs is collected for analysis. This is done as the minimum threshold serves as an indicator if the mission planning towards interstellar object is feasible or if the minimum Δv will be higher than current propulsion methods are capable of. In order to produce a diverse set of data points, the spacecraft is assumed to be launched not only from Earth but also from Sun-Earth Lagrange points, as well as Mercury and Venus, as well as combination of these points. The combination choice of Earth, L4 and L5 is chosen for widening the opportunities per each ISO, as well as to test if multiple spacecraft approach would be beneficial.

III. Delta-V Distribution

According to the above described simulation, the velocity distribution is generated based on which a density plots are created as seen in the Fig. 2 and 3. These plots represent the percentile of objects that each Δv add to the total 100% pool of generated objects.

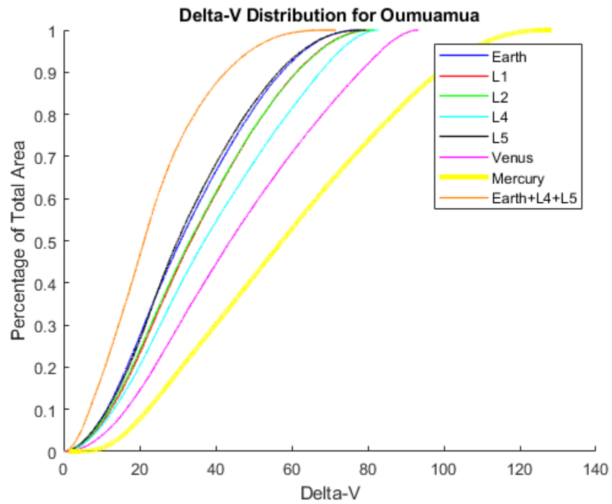

Fig. 2 Density of Delta-V cases for randomly generated Interstellar objects based on 'Oumuamua.

As can be observed within the Fig. 2 for 'Oumuamua based ISOs, the best opportunity to reach the objects brings the combination of Earth and Earth-Sun Lagrange points, which increases the reachable percentage of interstellar objects by $\Delta v = 10 km/s$ transfer from 7.911% to 17.711%. This increase results in nearly a fifth of objects being reachable, increasing the feasibility potential of a swarm mission. The same behavior of data can be observed within the Fig. 3 for Borisov, where the same percentage increase occurs.

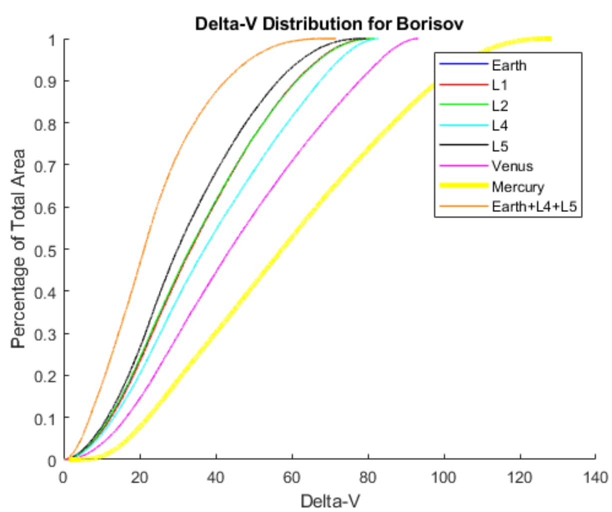

Fig. 3 Density of Delta-V cases for randomly generated Interstellar objects based on Borisov.

From all of the launch positions the least favorable resulted to be Venus and Mercury, with both increasing the needed $\Delta v's$ to reach the ISOs, as well as producing the least number of reachable objects for the $\Delta v = 10 km/s$ case.

IV. Time of Flight Distribution

Additional data analysis involves the distribution of Time of Flights, which for Fig. 4 and Fig. 5 as seen below has been cropped for 1 year period. This crop has been conducted due to assumption that most interstellar objects are unreachable after 1 year of flight.

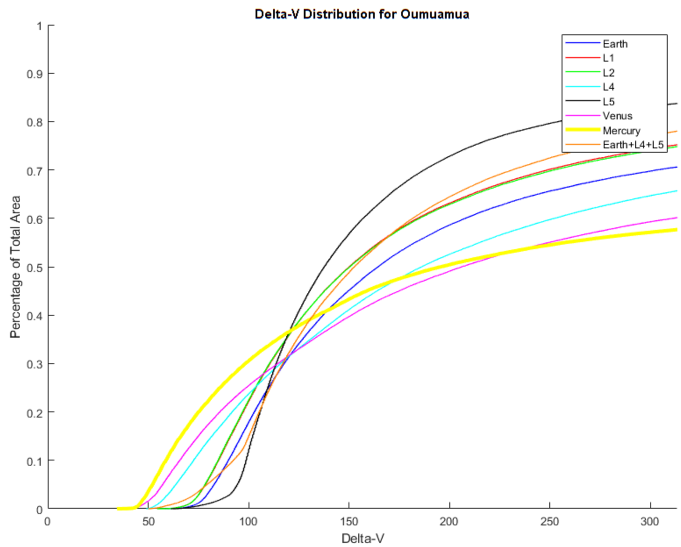

Fig. 4 Density of Time of Flight cases for randomly generated Interstellar objects based on 'Oumuamua.

Furthermore, when analyzing the reachable $\Delta v's$ with magnitude less than $10km/s$, the time of flights ranged from around 50 to 290 days, spanning nearly the entire year, of flight times for a potential mission. This provides a benefit for preparation and launch spacecraft as if the propulsion capabilities allowed higher $\Delta v's$ gains than $10km/s$ the same ISOs can be reached even with a certain delay. The delay analysis is aimed as the next step in the research, along with dynamic Earth movement. allowing for analysis of multiple consecutive launches from a single location.

For analyzing a feasibility of small spacecraft missions towards interstellar objects, an alternative range of TOFs for $\Delta v < 5km/s$ is produced, with the focus on observing how much the day range will change for a less capable spacecraft. For this change the time of flight range narrowed with minimum around 60 days and maximum around 220, which is still significant range to the controller, however, with this also the pool of reachable ISOs diminished below 3 percent for Earth. While this amount might still be satisfactory for a large pool of interstellar objects the $\Delta v < 10km/s$ range of velocities provides more chances to succeed in reaching the interstellar objects and conducting a mission.

V. Small Spacecraft

As mentioned one potential use case for the missions towards the interstellar objects is small spacecraft. These hold a huge benefit compared to the large spacecraft, as deployment can involve multiple of them for different positioning, which as seen in the figures above has resulted in a beneficial increase in reachable objects. Furthermore, the multi-spacecraft deployment can allow a swarm configuration to reach the interstellar object and conduct scientific measurements without worrying that singular spacecraft loss will result in failed mission. Additionally, a hybrid approach between these two can be applied with multiple spacecraft positioned in swarms at different locations, then based on the desired mission outcomes launching from multiple locations at the same time, for different view angles as well as different interception point chances. This approach would allow for multiple low cost spacecraft to be positioned within orbits around Earth, and L4, L5 Lagrange points for example, and upon detection launch towards it with different time of Flights, allowing for the first mission reaching the ISO to conduct an impact on its surface, while the consequent missions reaching the ISO observing the impacts outcome, collect samples or perform spectral imaging.

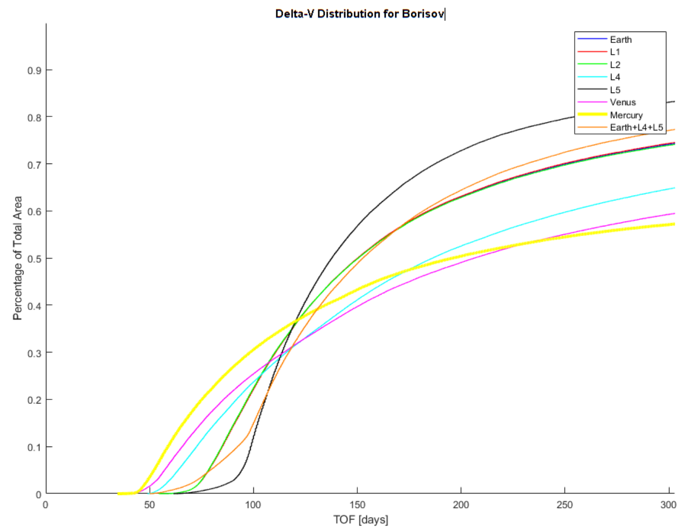

Fig. 5 Density of Time of Flight cases for randomly generated Interstellar objects based on Borisov.

A. Mission Feasibility

According to the above results and the initial look over different propulsion methods, the current types range from Chemical to Hall-Effect, alternating between high thrust forces but low ISPs for low thrust and very high ISPs respectively. For a small spacecraft the latter type would be more applicable, as it does not require as high fuel requirements as part of payload. However, depending on thruster capabilities, the flight time or burn time in order to reach the desired $\Delta v's$ might be higher than the time window to reach the interstellar object. This approach requires further in-depth study and optimization in order to find an optimal size for the spacecraft to minimize its costs, while allowing multiple of them to be launched, while providing plenty of payload space for instrumentation. Through this multiview approach, the spacecraft aimed at reaching the ISOs based on the initial set of Monte Carlo simulation, will require a propulsion technique capable of reaching $\Delta v = 5km/s$ within at most 200 days, assuming no delay on launch, and 50 days or less if desired to apply a delay to the launch, which is still necessary to be analyzed.