Project Lyra: Catching 1I/Oumuamua – Mission Opportunities After 2024

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Abstract
In October 2017, the first interstellar object within our solar system was discovered. Today designated 1I/Oumuamua, it shows characteristics that have never before been observed in a celestial body. Due to these characteristics, an in-situ investigation of 1I would be of extraordinary scientific value. Previous studies have demonstrated that a mission to 1I/Oumuamua is feasible, using current and near-term technologies. However, the anticipated launch date of 2020-2021 is too soon to be realistic. In this paper, we demonstrate that a mission to 1I/Oumuamua is feasible at an even later point in time, providing sufficient time for developing a spacecraft. Using the OITS trajectory simulation tool, various scenarios are analyzed, including a powered Jupiter flyby and Solar Oberth manoeuvre, a Jupiter powered flyby, and more complex flyby schemes including a Mars and Venus flyby. With a powered Jupiter flyby and Solar Oberth manoeuvre, we identify a trajectory to 1I/Oumuamua with a launch date in 2033, a total velocity increment of 18.6 km/s, and arrival at 1I/Oumuamua in 2049. With an additional deep space manoeuvre before the powered Jupiter flyby, a trajectory with a launch date in 2030, a total velocity increment of 16.2 km/s, and an arrival at 1I/Oumuamua in 2047 were identified. Both launch dates would provide over a decade for spacecraft development, in contrast to the previously identified 2020-2021 launch dates. We conclude that a mission to 1I/Oumuamua is feasible, using existing and near-term technologies and there is sufficient time for developing such a mission.

1. Introduction
1I/Oumuamua is the first interstellar object that has been observed within our Solar System [1–3]. Since its discovery in October 2017, 1I/Oumuamua has generated considerable interest from both academia and the media. The academic debate is still ongoing and topics are as wide-ranging as the object’s shape [4–9], its composition [4,5,10–14], its origin [15–21], explanation for an observed acceleration [22,23], and estimates for the population of similar objects [2,5]. Given that 1I/Oumuamua is the first confirmed interstellar object that has been discovered intercepting our Solar System, it might turn out to be the only opportunity to study interstellar material in-situ for decades or even centuries to come [2,5]. Could a spacecraft be sent to 1I and collect scientific data in-situ? Seligman and Laughlin [24] have previously concluded that missions to objects similar to 1I would be feasible but dependent on an early detection and early launch. Hein et al. [25,26] have argued that a mission to 1I would be feasible, using existing and near-term technologies and a combination of a powered Jupiter flyby and a solar Oberth manoeuvre. However, the optimal determined launch date between 2020 and 2021 is deemed to be very challenging from an engineering point of view, as the development of interplanetary spacecraft takes at least 5 and often more than 10 years. Therefore, one of the key questions regarding the feasibility of a mission to 1I is whether or not missions with a launch date at least 5 years into the future (2024 onwards) are feasible in terms of mission duration and velocity requirement ΔV.

This paper aims at addressing the question of the feasibility of a mission to 1I/Oumuamua in 2024 and beyond.
2. Materials and Methods

For finding trajectories with a sufficiently low $\Delta V$ and acceptable mission duration, various optimal flyby configurations are analyzed. As a cut-off criteria for $\Delta V$, we select 18.3 km/s from Hein et al. [26]. This $\Delta V$ allows for reasonably sized spacecraft masses for existing or near-term launch systems such as the Falcon Heavy and the Space Launch System. For the maximum flight duration from launch to 1I/’Oumuamua encounter, we somehow arbitrarily select 30 years, as it stays within the career of scientists who have worked on the formulation of the mission at the beginning of their career.

The trajectories are calculated using the Optimum Interplanetary Trajectory Software (OITS) developed by Adam Hibberd, based on a patched conic approximation. With the patched conic approximation, only the gravitational attraction of a celestial body is taken into consideration within its sphere of influence and the gravitational attraction of other bodies is neglected. The trajectory connecting each pair of celestial bodies is determined by solving the Lambert problem using the Universal Variable Formulation [27]. The resulting non-linear global optimization problem with inequality constraints is solved applying the NOMAD solver [28].

In the following investigations, total $\Delta V$ is defined as the sum of the hyperbolic excess speed at Earth with the absolute value of each of the $\Delta V_i$’s calculated at subsequent planetary encounters. These $\Delta V_i$’s are assumed to be impulsive, in-plane and at the periapsis point with respect to each planet in turn. An exception is where an encounter is specified as an ‘Intermediate Point’ (IP). An IP is a point of zero mass with user-specified distance away from the centre of the ecliptic whose polar angles $\theta, \phi$ are additional optimization parameters for the NOMAD solver. An IP corresponds to a Deep Space Manoeuvre (DSM). The $\Delta V_i$ at an IP is defined as the magnitude of change in velocity required at the IP to take the spacecraft from body i-1 to body i+1 via the IP – thus the notion of periapsis is not applicable for such an encounter. At destination, a flyby of 1I is assumed and so the final $\Delta V_i$ is zero. For deriving celestial body positions and velocities as a function of time, the NASA NAIF SPICE Toolkit is used and corresponding binary SPK files are utilised.

For all planetary encounters a minimum periapsis altitude of 200km is specified relative to the planet’s equatorial radius. In the case of Jupiter, this equatorial radius is taken at the 1bar level, i.e. 71492km.

In this paper, we add results for the long-term evolution of the total $\Delta V$ for the trajectory Earth-Jupiter-solar Oberth manoeuvre-1I/’Oumuamua (E-J-3SR-1I). For comparison purposes, it was decided that trajectories directly from Jupiter to 1I, without a Solar Oberth Manoeuvre between Jupiter and 1I, should be analysed, i.e. X–J–1I (where X is some combination of planetary encounters beginning at Earth). The reasoning for this is that as the heaviest planet in the Solar System, it is the planet best placed for achieving maximum benefit from the ‘Oberth Effect’. The Oberth Effect holds that in the presence of a gravitational well, the total energy change of an orbiting spacecraft induced by a change in velocity $\Delta V$ of the spacecraft, reaches a maximum at the shortest distance and fastest speed with respect to the centre of attraction, i.e. at periapsis. For a spacecraft on an escape orbit, this change in energy manifests as a change in the hyperbolic excess speed of the body. Thus a high hyperbolic excess speed can be achieved for a low $\Delta V$. For the high heliocentric speeds necessary to catch up with 1I/’Oumuamua, as large a gravitational well as possible must be chosen to make the most of the Oberth Effect.

Finally, by analysing missions from Mars to Jupiter to 1I/’Oumuamua (M-J-1I) (with Mars as the home planet) it was determined that a propitious relative positioning of Mars and Jupiter occurred with a rather late Jupiter arrival in 2032. This could potentially offer an opportunity for missions from Earth to Mars with a later launch than those detailed above and consequently allow a longer mission preparation time. Thus missions with Mars as the last visit before Jupiter and then 1I/’Oumuamua were investigated.
3. Results

3.1 Jupiter flyby – Solar Oberth manoeuvre trajectories between 2020-2060

The original Project Lyra [26] paper discussed an Earth to Jupiter to 3 Solar radii to 1I trajectory (E-J-3SR-1I), employing a Solar Oberth manoeuvre, launching in 2021. The favourable timing of this trajectory relies on:

(a) the propitious positioning of Jupiter (in its 11.9 year orbit around the Sun) relative to 1I.
(b) the close conjunction of Earth and Jupiter, at respectively launch and Jupiter arrival, such as to make optimal use of Earth’s orbital velocity.

As is clear from Hein et al. [26], (a) and (b) conspire to allow a minimum total ΔV of around 18.3km/s with a launch in 2021.

Figure 1 shows the long-term results for the total ΔV for this E-J-3SR-1I trajectory. As one might expect, there is a period of 12 or so years between successive coincidences of (a) and (b), with minima lasting for 4 years or so. Note mission duration is not constrained for these calculations, so corresponding mission durations shown in Figure 2 are optimal ones in terms of ΔV. It can be seen that for a launch in 2033, a flyby of 1I can be achieved with a mission duration of 16 years and a ΔV of roughly 20 km/s. Developing a spacecraft for a launch in 2033 is entirely within the range of typical development durations of interplanetary spacecraft and feasible from an engineering point of view.

![Figure 1: Minimum ΔV trajectories to 1I/Oumuamua for E-J-3SR-1I](image)

As can be seen in Figure 1, even a much later launch date is possible in 2045 with a mission duration of 26 years. This would provide about 25 years for developing and launching a spacecraft. The corresponding ΔV is close to the 2033 launch of 20 km/s. A much later launch date in 2057 would be possible, however, it would exceed the maximum acceptable mission duration of 30 years by about 7 years. However, if longer mission durations are considered acceptable, a launch in 2057 would be another alternative.
To summarize, there are several additional opportunities of launching a spacecraft to 1I/'Oumuamua post 2024 with opportunities in 2033, 2045, and 2057. The ΔV of about 20 km/s could be achieved by a combination of powered Jupiter flyby and solar Oberth manoeuvre, using existing or near-term technologies, as has already been demonstrated in Hein et al. [26]. For example, a Falcon Heavy could launch a spacecraft of about 37 kg to 1I/'Oumuamua and a SLS launcher a 122 kg spacecraft, respectively.

### 3.2 Jupiter flyby – Solar Oberth Manoeuvre tranjectories with Deep Space Manoeuvre

To use the architecture suggested by KISS [29], a DSM was inserted at 3.2AU after Earth launch (launch being in 2030, i.e. 3 years before the optimal launch year found in the preceding section), then an Earth return followed by Jupiter, 3 Solar radii and then on to 1I. Thus E-DSM-E-J-3SR-1I. The E-DSM-E component represents a round trip of about 3 years and is the reasoning behind setting the DSM at 3.2AU. This yielded a total ΔV of 16.2 km/s, an appreciable improvement on E-J-3SR-1I. The time from launch to 1I encounter would be about 17 years. Refer to Figure 3 for the E-DSM-E-J-3SR-1I trajectory.
3.3 Direct Trajectories from Jupiter to 1I/’Oumuamua

The simplest mission sequence is Earth to Jupiter to 1I, i.e. E-J-1I with a Jupiter Oberth manoeuvre. A mission duration of 20 years was selected. Results indicate an optimal launch in 2031 February with a \( \Delta V \) of around 26.5 km/s and arrival in 2051. We shall call this scenario (A):

Scenario (A): E-J-1I (Mission Duration=20years.)
Launch 2031 FEB 10
\( C3=96.77 \text{km}^2/\text{s}^2 \)
\( \Delta V \) at Jupiter = 16.7km/s
Total \( \Delta V = 26.5 \text{km/s} \)

Ideally, this needs to be reduced to less than 18.3 km/s to make the mission a viable alternative to the E-J-3SR-1I scenario. Tackling this problem, it seems that the main hurdle is the large \( \Delta V \) for the Jupiter Oberth manoeuvre, required to get to 1I. It appears that if this can be reduced and the majority of the \( \Delta V \) can be placed at Earth, then this Earth \( \Delta V \) can potentially be diminished by a combination of gravitational assists of the inner planets, i.e. Venus, Earth & Mars.

Can the plane of the orbit arriving at Jupiter be modified altering the Jupiter Oberth manoeuvre opening angle such as to enable lower \( \Delta V \) values? The problem is that the trajectory from Earth to Jupiter is approximately in the ecliptic plane. An attempt to make the plane of the orbit from Earth to Jupiter outside of the ecliptic was explored. (This can be done in OITS by specifying the radial distance from the Sun of an ‘Intermediate Point’ [IP], otherwise known as a Deep Space Manoeuvre [DSM], between
Earth and Jupiter, whose ecliptic polar angles are then optimized with the various other optimization parameters). This met with marginal success with a radial distance set to 4.9AU. Thus the E-J-I orbit trajectory for launch 2031 had a $\Delta V$ of 26.5km/s whereas with a DSM at 4.9AU this reduced to around 24.3km/s:

Scenario (B): E-DSM-J-I (Mission Duration=20years.)
Launch 2031 FEB 25
C3=94.26km2/s2
$\Delta V$ at DSM =2.4km/s
$\Delta V$ at Jupiter = 12.2km/s
Total $\Delta V$ = 24.3km/s

Clearly the $\Delta V$ at Jupiter has reduced but is there scope for reducing this further? To this end, a Jupiter return was considered - arrival at Jupiter from Earth is followed by a half Jupiter-year return of approx. 6years and achieving a distance of 5.2AU significantly out of the ecliptic. This Jupiter-Jupiter transfer could potentially have a large inclination and make inroads into the opening angle at the Jupiter return. Here are results for E-J-DSM-J-I, Scenario (C).

Scenario (C): E-J-DSM-J-I (Mission Duration 27years.)
Launch 2024 AUG 24
C3=141.6km/s
$\Delta V$ at Jupiter = 0km/s
$\Delta V$ at DSM =1.4km/s
$\Delta V$ at Jupiter Return = 9.4km/s
Total $\Delta V$ = 22.8km/s

This seems to have met with some success in that now the $\Delta V$ at Jupiter has significantly reduced and Earth C3 has increased. This looks promising in that a combination of inner planet gravitational assists which will improve on the $\Delta V$ to get to Jupiter can be sought.

Thus the sequence X-J-DSM-J-I was investigated. Table 1 summarises these missions. Here is such a trajectory with an Earth return after 1 year then heads off towards Jupiter and returns to Jupiter (5 in Table 1):

Scenario (D): E-E-J-DSM-J-I (Mission Duration 28 years.)
Launch 2023 AUG 22
C3=0km/s
$\Delta V$ at Earth Return= 5.6km/s
$\Delta V$ at Jupiter = 0.0km/s
$\Delta V$ at DSM =1.4km/s
$\Delta V$ at Jupiter Return = 9.4km/s
Total $\Delta V$ = 16.4km/s

Refer to Figure 4. Mission scenarios (C) and (D) both have return trips to Jupiter lasting 2200 days or so, i.e. half a Jupiter year. This allows a high inclination transfer orbit w.r.t. the ecliptic. However on further investigation of the X-J-DSM-J-I combination, a benefit was also observed for return trips lasting a much shorter time than this - and with low inclinations with respect to Jupiter - refer to the trajectories (6) & (7) in Table 1. Note (7) is basically the same passage to Jupiter as the ESA planned JUICE mission in 2022 and is an extremely efficient trajectory – refer Figure 5.

The results are obtained by using an additional error estimation code for OITS, as OITS assumes arrival at DSM between Jupiter arrival and return, is outside Jupiter’s Sphere of Influence (SOI) and travelling with a small velocity relative to Jupiter. As Jupiter’s SOI is extremely large, i.e. Laplace SOI=0.3AU
from Jupiter, and in fact on returning to Jupiter, the spacecraft has been loitering within this SOI and has a significantly non-zero component. The ΔV’s calculated by OITS have to be increased by around 4 km/s at the DSM for these ‘-J-DSM-J-1I’ trajectories. This error has been taken into account for (6) and (7).

Figure 4: E-E-J-DSM-J-1I trajectory

Although this trajectory has the lowest ΔV of all studied trajectories in this paper, one key drawback is the launch date in 2023, which is too short notice for developing and launching a spacecraft, using current engineering practice. Furthermore, although the time from launch to 1I/’Oumuamua encounter of 28 years is within the limits of 30 years, it is clearly less attractive than the durations from Section 3.1.

3.4 Missions to Mars followed by Jupiter and then 1I/’Oumuamua
A fruitful sequence appears to include Mars flybies, i.e. E-M-DSM-M-J-1I, shown in Figure 5. With DSM at approximately Mars’ radial distance, i.e. 1.523AU. Thus after arriving at Mars from Earth, some time is spent loitering in the vicinity of Mars before a return and then an encounter with Jupiter.
Figure 5: E-E-V-E-M-E-J-IP-J-II trajectory

3.5 Summary of Results

Table 1 provides an overview of the trajectories presented in this paper. The launch dates are between 2022 and 2033 and the arrival dates at 1I/ʻOumuamua are between 2047 and 2052.

Table 1: Summary of scenarios

| Mission     | Launch Earth | Arrival at 1I | Arrival At Jupiter prior to 1I | Loiter Time [days] | Mission Duration [years] | C3 at Earth [km/s²] | Total ΔV [km/s] | ΔV Prior to First Jupiter Encounter [km/s] | ΔV After including first Jupiter Encounter [km/s] |
|-------------|--------------|---------------|-------------------------------|--------------------|-------------------------|---------------------|----------------|----------------------------------|--------------------------------------------|
| 1           | E-J-3SR-11   | 2033 MAY 08   | 2049 APR 25                   | 2034 AUG 10        | N/A                     | 16                  | 116             | 18.6                             | 10.8                                       | 7.8                                       |
| 2           | E-DSM-E-J-3SR-11 | 2030 APR 07   | 2047 SEP 01                   | 2034 JUL 08        | N/A                     | 17                  | 49              | 16.28                            | 8.4                                        | 7.8                                       |
| 3 (Scenario A) | E-J-II       | 2031 FEB 10   | 2051 FEB 05                   | 2033 AUG 09        | N/A                     | 20                  | 97              | 26.5                             | 9.8                                        | 16.7                                      |
| (Scenario C) | E-J-DSM-J-I | 2024 AUG 24 | 2051 AUG 18 | 2031 DEC 22 | N/A | 27 | 142 | 22.7 | 11.9 | 10.8 |
|-------------|-------------|-------------|-------------|-------------|-----|----|-----|------|-----|-----|
| 5* (Scenario D) | E-E-J-DSM-J-I | 2024 AUG 22 | 2051 AUG 15 | 2031 DEC 25 | N/A | 28 | 0.0 | 16.4 | 5.6 | 10.7 |
| 6* | E-E-V-E-M-E-J-DSM-J-I | 2024 OCT 01 | 2051 SEP 25 | 2032 MAR 22 | 850 | 27 | 0.0 | 20.7 | 3.7 | 16.9 |
| 7* | E-M-DSM-M-J-I | 2022 MAY 31 | 2051 MAY 24 | 2029 MAY 10 | 1017 | 29 | 0.0 | 18.9 | 2.2 | 16.7 |
| 8 | E-M-DSM-M-J-I | 2028 DEC 15 | 2052 DEC 09 | 2032 MAR 05 | 417 | 24 | 9.4 | 21.9 | 10 | 11.9 |
| 9 | E-E-M-DSM-M-J-I | 2027 DEC 13 | 2051 DEC 07 | 2032 FEB 08 | 471 | 24 | 0.0 | 19.8 | 11 | 8.8 |

*a Deep Space Manoeuvre is at 3.2AU from Sun.

*b First Deep Space Manoeuvre is at 2.2AU from Sun.

c Earth return 1 year after launch i.e. E-E-

d Loiter time in vicinity of Jupiter

e Loiter time in vicinity of Mars

From Table 1, it can be seen that there is a trade-off between total ΔV and mission duration. The Pareto frontier for the two values is depicted in Figure 6, where scenario E-J-3SR-I (launch in 2033) and E-DSM-E-J-3SR-I (launch in 2030) are Pareto optimal. Both scenarios would allow for ample time for spacecraft development.
4. Conclusions

This paper presented a feasibility analysis of a mission to 1I/’Oumuamua using current and near-term technologies with a launch date in the mid-2020s to mid-2030s, which would allow for sufficient time for spacecraft development. We identify at least two missions to 1I/’Oumuamua with launch dates between 2030 and 2033 with total velocity increments of 16.2 km/s and 18.6 km/s, and an arrival at 1I/’Oumuamua in 2047 and 2049, respectively. These launch dates also provide about a decade for spacecraft development from 2019 onwards, in contrast to the previously identified launch dates in the 2020-2021 timeframe, where only 1-2 years are left for spacecraft development. For future work, we propose a conceptual design of the associated spacecraft and corresponding instrument suite.

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