Design of Interplanetary Missions to Jupiter Using Optimum Interplanetary Trajectory Software

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When Adam Hibberd developed the first version of his ‘Optimum Interplanetary Trajectory Software’ (OITS). He has, as its name implies, intended it for interplanetary missions. The appearance of Oumuamua and his contact with i4is gave it a new and unforeseen purpose. Here he explains an application of OITS to its original purpose.

In 2017 I developed the software application ‘Optimum Interplanetary Trajectory Software’ (OITS). By the time the first interstellar object 1I/’Oumuamua was discovered passing through our solar system, I had completed most of the work. Inspired by the Arthur C Clarke novel ‘Rendezvous with Rama’ I decided to exploit OITS to perform research into missions to ‘Oumuamua. I was soon generating interesting and important results and decided to contact the UK non-profit, the ‘Initiative for Interstellar Studies’ (i4is), becoming a member of the ‘Project Lyra’ team, and collaborating with them on various papers on the subject.

The article here is not related to anything interstellar. I had originally intended OITS to study missions to bodies belonging to our solar system, and indeed if used judiciously, OITS can be a powerful tool for preliminary interplanetary mission design.

Recently I conducted a little research into missions to Jupiter as this is relevant to two missions which will be launched later in this decade. The research was on a small scale, so not really worthy of a paper (and actually a paper already exists on the subject anyway), nevertheless what follows is intended as an education as to how to use OITS, as well as an invitation to you to try it out for yourself.

Two spacecraft will be launched in the next couple of years or so bound for the gas giant Jupiter, the largest planet in our solar system and approximately 1,000th the mass of the sun. As far as the interplanetary missions are concerned the target is Jupiter. However, because most of the attention of these spacecraft will be directed on three of Jupiter’s moons, Europa, Ganymede and Callisto, the planet Jupiter will actually just be the background setting. The spacecraft in question are the European Space Agency’s (ESA) JUICE mission (a clumsily constructed acronym of JUpiter ICy moon Explorer) and the NASA Europa Clipper.

Mission planners will be crossing their fingers that everything will be ship-shape, however both these probes owe their existence to a previous Jupiter mission which was a partial failure, the Galileo spacecraft launched some time ago, in 1989 by space shuttle Atlantis. Space enthusiasts may recollect that the high-gain antenna of the Galileo craft failed to deploy, and consequently the low-gain antenna had to be used in its stead, significantly hampering the scientific return garnered from the mission.

Nevertheless despite this setback, Galileo was still able to use its onboard instrumentation, and, as a result of the measurements and images it took of Europa, scientists now believe there to be a subsurface ocean of salty liquid water present in the

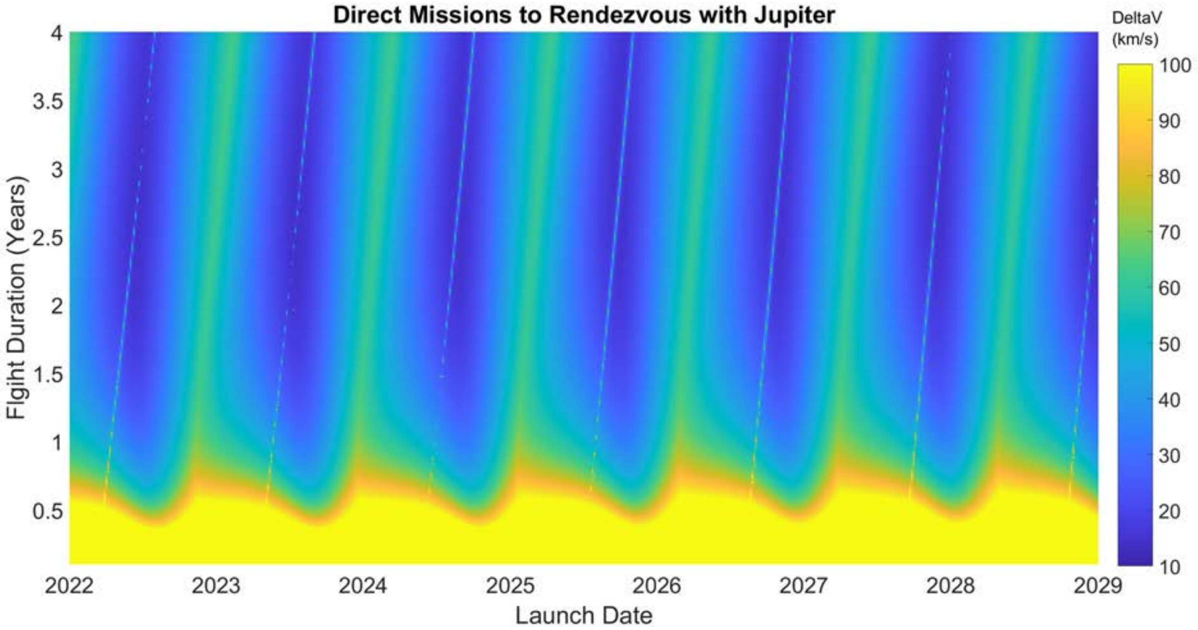

Figure 1

interior of this Galilean moon. Furthermore, hydrothermal vents may exist which are known to support an abundance of life on Earth.

In addition to Europa and Enceladus, a moon of Saturn must in my view be considered a high priority for in-situ research. Also two further moons of Jupiter, Callisto and Ganymede (the solar system's largest moon) may support similar subsurface environments and indeed the JUICE mission is set to explore these three Galilean moons.

Before we begin, there are certain assumptions which OITS adopts, the overarching one is of a series of instantaneous applications of ΔV placed at the closest approach (the periapsis point) of the spacecraft at each of the planets encountered and in line with the spacecraft's apsidal velocity. This assumption amounts to infinite thrust which may seem rather outrageous. However chemical propulsion does indeed have high thrust compared to many other propulsion schemes. Furthermore when one compares the rocket burn time with the long durations of interplanetary orbital arcs between planetary encounters, this assumption of impulsive thrust is really quite realistic, yielding results more than satisfactory for preliminary mission design of the kind we shall conduct here, comparing favourably with NASA's online Trajectory Browser for instance.

OITS makes no coplanar assumption nor one of circularity, this is because it uses position and velocities of celestial bodies generated by the NASA JPL NAIF SPICE toolkit which is linked in with OITS as third party software. Consequently the 'ephemerides' calculated are extremely accurate and factor in all the major forces exerted on the planets as they 'wander' around the sun.

So that the analysis here is relevant to the JUICE and Europa Clipper missions, we shall analyse launch opportunities no earlier than January 2022 and no later than January 2029, and determine whether we can find any promising interplanetary mission profiles. We may discover a combination of GAs (gravitational assists) superior to those which ESA or NASA have selected. This superiority could manifest as either a lower ΔV or alternatively a reduction in the flight time needed.

Firstly the 'direct scenario'. This is the simplest option, also the reference for alternative indirect routes – if the total ΔVs with GAs are higher than this most direct and simplest of cases, then such trajectories can be discounted as inferior and irrelevant. For the direct case, a colour contour – or 'pork chop' plot is extremely useful (and most visually satisfying) as it neatly illustrates in patterns of colour, the alignments of the two planets - refer to Figure 1. Referencing the numerical results, we find the total ΔV (which we define as the sum of the hyperbolic excess speed at Earth, V∞, and the

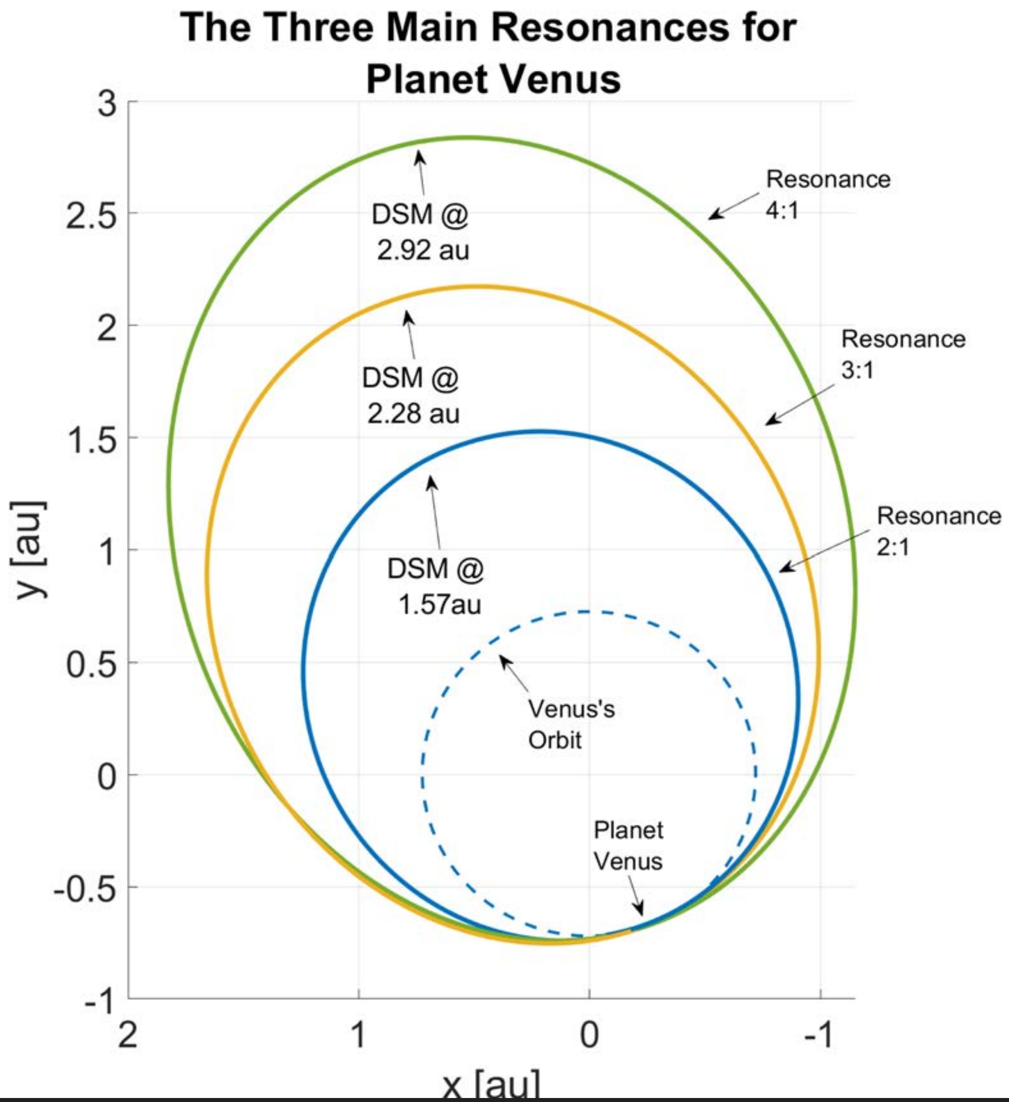

Figure 2

arrival speed relative to Jupiter, Varr) has a minimum of 8.7+5.7=14.4 km/s and the flight duration is around three years. In the following we shall study some GA scenarios which might bring this ΔV down, but on the other hand might extend the flight duration.

We can first attempt a single GA of Venus and compare it with a single GA of Mars. We find the results to be unpromising in that for both cases, the total ΔV offers no particular improvement over the direct case with no appreciable reduction in flight time. For Venus a possible launch might be on January 2025 with a ΔV = 15.4 km/s, and for Mars it would be December 2028, with a ΔV=14.7 km/s. These results indicate that further GAs are required for both cases, one alone is not sufficient.

Let us address Venus first, as this opens up further opportunities for GAs of two inner planets, ie Earth or Mars, or indeed a return to Venus, for an additional GA there. We can exclude Mercury because the task of getting there is laden with ΔV difficulties, owing to its closeness to the sun. When an E-V-E-J scenario is entered into OITS, the results again are unpromising, with no missions in the launch interval 2022-2029 which offer advantage over the direct case.

However when we switch to a return to Venus, ie E-V-V-J, things start to fall into place. A note here regarding the V-V segment of the journey. The situation is that the spacecraft departs Venus, reaches an aphelion point where a Deep Space Manoeuvre takes place, and then returns to Venus, conducts a GA of Venus, and finally heads off towards Jupiter. So in fact to be more accurate, this should be abbreviated as E-V-DSM-V-J. The minimum ΔVs for such an arrangement occur when the spacecraft's orbit in the V-DSM-V segment is in a resonance with Venus, so the travel time equals N Venus cycles, where N is a whole number. For OITS we can ensure this by introducing an Intermediate Point, whose distance away from the sun can be user-

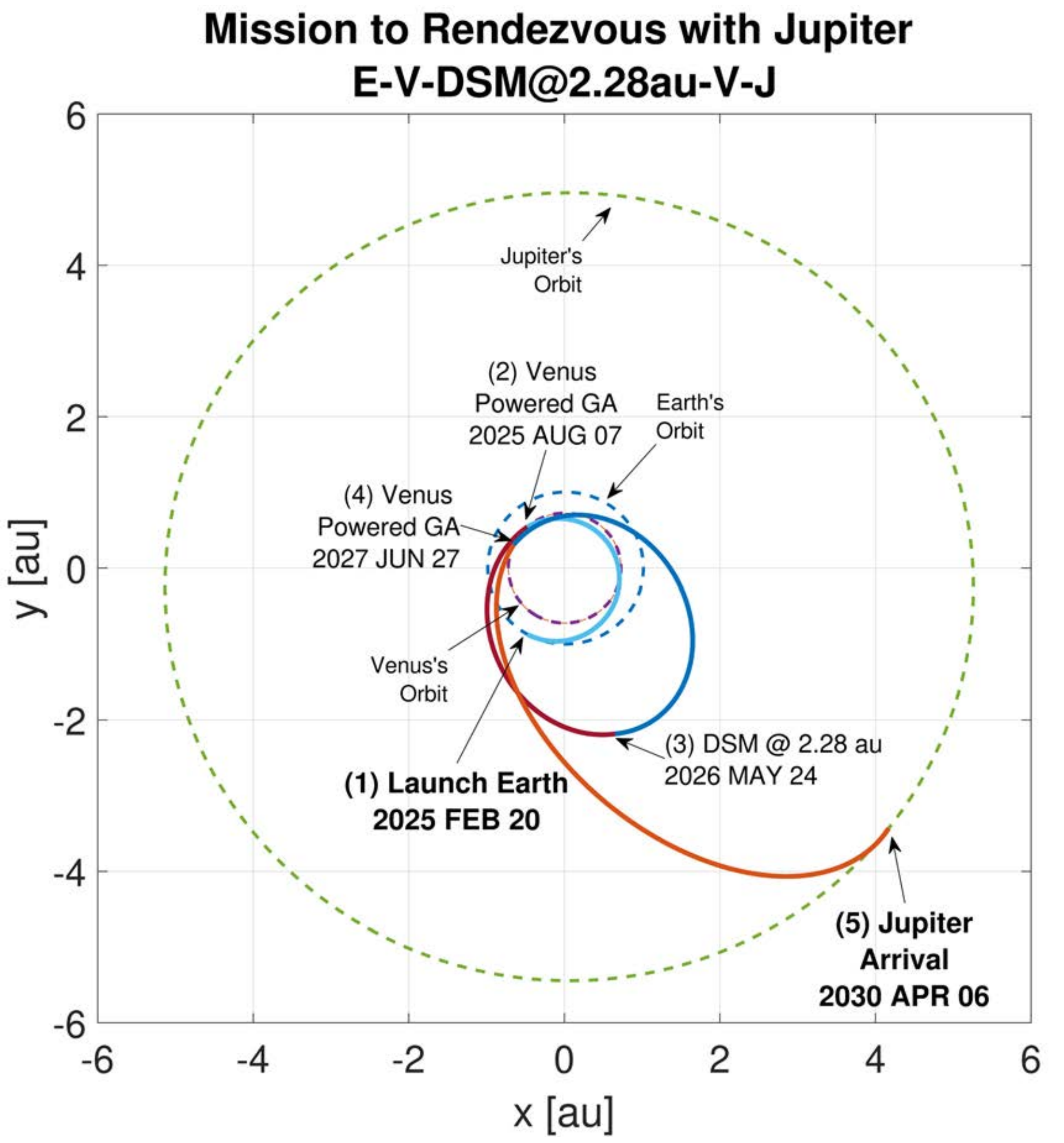

Figure 3

specified to OITS. These resonances and their aphelia distances are illustrated in Figure 2

In the case of the Cassini mission to Saturn, it exploited a Venus resonance of N=2, so we shall attempt N=2 for the E-V-DSM-V-J trajectory, as well as N=3 & N=4. The result? N=3 is the optimal choice with ΔV=12.1 km/s, shown in Figure 3.

But why not try two Venus return segments in the form of E-V-DSM-V-DSM-V-J, with the aphelion of the second encounter greater than the first? I tried this with first N=2 and N=3 and found a launch on 2026 SEP 18 (ΔV=14.3 km/s) arriving 2033. When we try N=2 followed by N=4, OITS calculates a launch date in 2023 MAY 11 (ΔV=11.3 km/s) and arrival in 2030. Thus we have in the latter case a slightly lower ΔV than the trajectory of Figure 3.

In addition, we could introduce Earth returns using

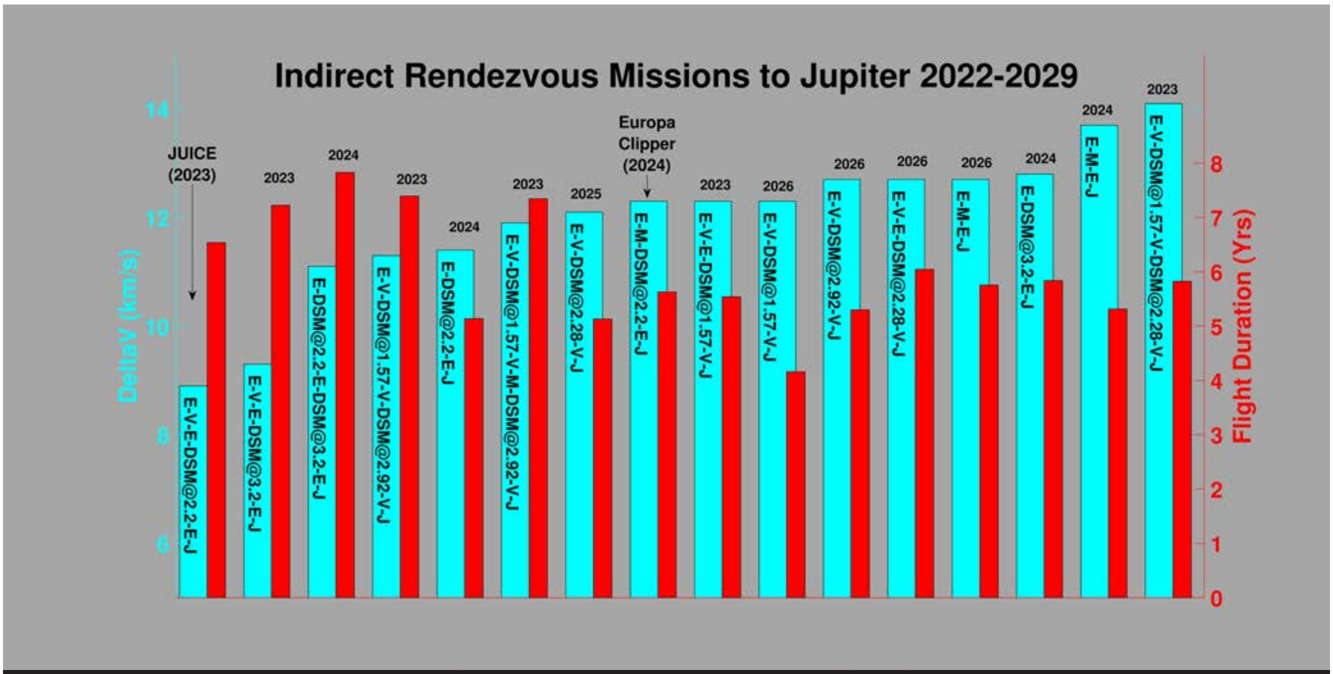

Figure 4

a resonance for the Earth return encounter in a similar vein to that exploited for the Venus return. The results of all these investigations are presented as a bar chart in Figure 4.

The cyan bar for each mission is the ‘Total ΔV’ (left axis) equal to the sum of the hyperbolic excess required at Earth and all the in-flight ΔV burns, including that required to rendezvous with Jupiter (in other words match velocities with it). The trajectories are ordered from least ΔV at the left, to most ΔV on the right. The red bars are flight duration in years (right axis). Those trajectories worse than the direct solution are not shown. NB I cannot declare this to be an exhaustive list.

The original plan for JUICE was a launch in 2022 with trajectory E-E-V-E-M-E-J. This option is excluded from Figure 4 as it has probably been rejected due to delays in the preparation of the JUICE spacecraft. With an in-flight ΔV of only around 1 km/s, this would have been almost a freeride to Jupiter. If we reject this mission scenario, then we see the JUICE backup mission to be adopted in the eventuality of delays (on the extreme left), is the most efficient with a launch over a year later, in 2023, and an arrival around the same time as the original mission plan. This is similar to the Galileo ‘VEEGA’ combination. The Galileo ‘VEEGA’ trajectory was proven to be the theoretically most efficient Jupiter mission scenario available in the timescale of the Galileo launch. A difference is that for JUICE, there is an initial slingshot of Earth’s Moon to lower ΔV and so leverage mission payload mass. As OITS cannot model moon encounters, Figure 4 provides the closest OITS can achieve.

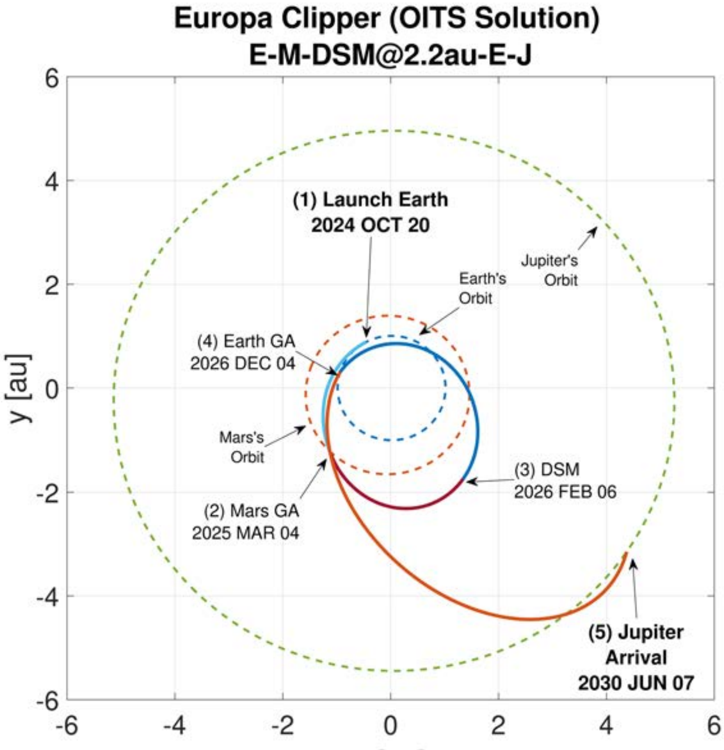

Figure 5

What about the Europa Clipper? Here we are presented with a little conundrum in that the trajectory chosen by NASA - refer Figure 5 - is way down and 8th on the list. Let us say that the Clipper's timeline for preparation ruled out any mission earlier than 2024, this would exclude the first two trajectories, but what of trajectory 3? This conundrum is partially yet not fully resolved when we do some further calculations.

Let us assume that the Clipper will have an onboard chemical rocket with the hypergolic combination of propellants hydrazine and nitrogen tetroxide, generating an exhaust velocity of approximately I=3.35 km/s. This system would be able to supply all the in-flight ΔVs, denoted here as ΔVif, for the interplanetary journey. Using the inverse of the Tsiolkovsky equation, we can calculate how much mass would be remaining after the in-flight burns have been executed:

$$M_D = M_0 \, exp\left(-\frac{\Delta V_{if}}{I}\right)$$

Where M0 here is the initial mass of the spacecraft. Figure 6 is a bar chart similar to Figure 4 except the cyan bars represent MD for the Falcon Heavy expendable launcher for each mission profile.

We see on this basis, the Delta Clipper moves up a couple of places, however mission 3 in Figure 4 remains the superior option. So why did NASA reject mission scenario 3 in favour of 8 from Figure 4? I am currently not in on any decision-making NASA meetings for Delta Clipper, but it could simply be a matter of launch window. Mission 3 has a launch right at the beginning of 2024, in January, whereas mission 8, the route selected by NASA, affords more time for preparing the spacecraft, 9 extra months. Two further points are (a) the spacecraft arrives at

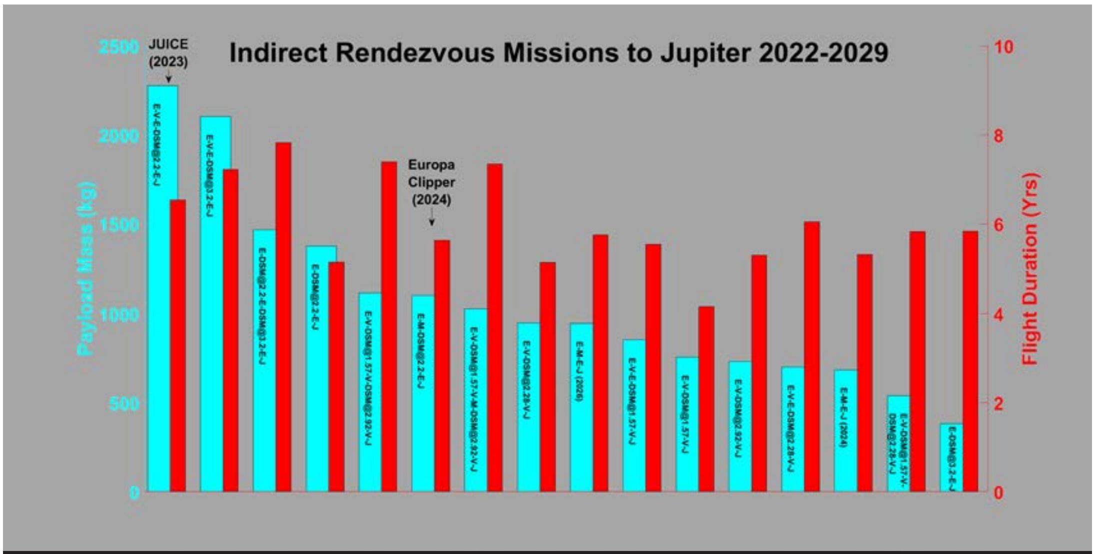

Figure 6

Jupiter before the alternative of mission 3 (though of course with less useful payload mass than mission 3) and (b) mission 8 requires no ΔV application en-route, except that for rendezvous with Jupiter.

I trust this has been an instructive insight into the design of interplanetary trajectories using OITS and you have come away with some appetite for more.

Are we alone in this Universe? Is Earth an oasis in an otherwise barren desert? Well if we were to find biosignatures - and then perhaps even life - on one of Jupiter's moons, or indeed Enceladus, then surely the prospect of the universe supporting an abundance of life would increase immeasurably. When Galileo observed the moons of Jupiter, was he unwittingly the first human to observe an inhabited alien world? The only way to answer these questions is to go there and I am proud that OITS can assist in this noble quest.

If you wish to view trajectory videos for these missions, as calculated by OITS go to:

GALILEO:
www.youtube.com/watch?v=Xa2iYAcsv34
JUICE #1:
www.youtube.com/watch?v=1K_fefX8yZo
JUICE #2:
www.youtube.com/watch?v=FjPH8zrUwF4
EUROPA CLIPPER:
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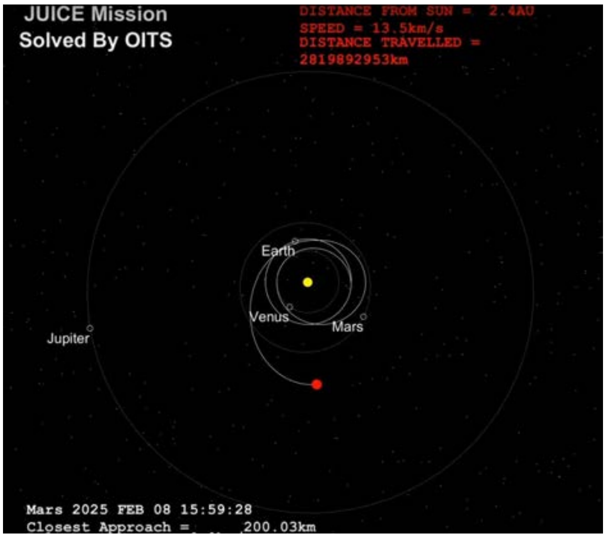
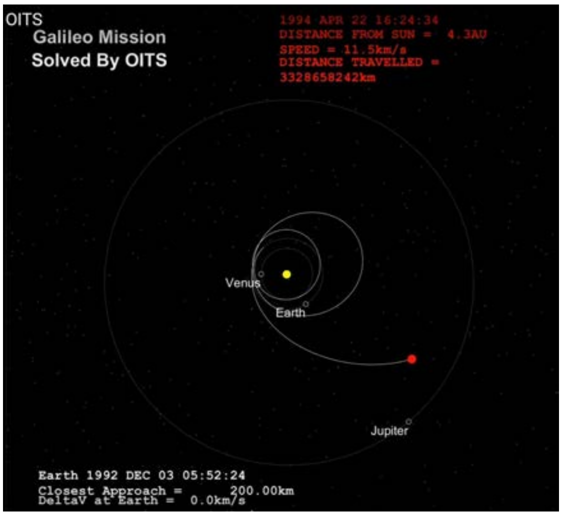
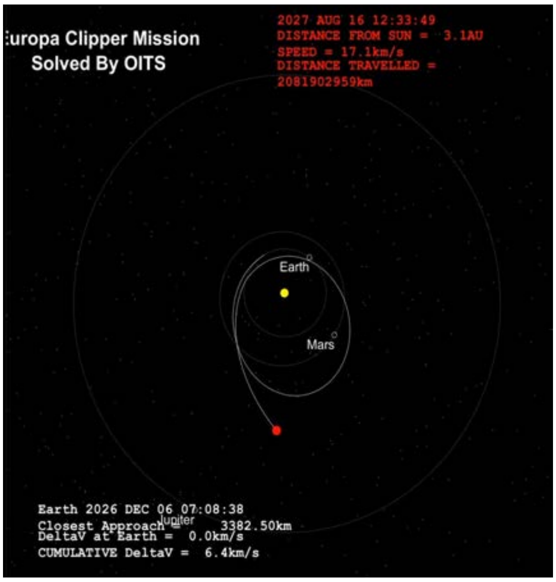
trajectory videos for three missions, as calculated by OITS







Adam Hibberd is the lead astrodynamicist for i4is. He has been an author of 16 papers in this and related topics in the past three years, many of them published in leading journals including Acta Astronautica, Advances in Space Research, The Astrophysical Journal Letters and the Bulletin of the American Astronomical Society. Adam was educated at a UK state school, Stoke Park Comprehensive School and Community College, in Coventry. He has a joint honours degree in physics and maths from the University of Keele. He worked in the '90s as a software engineer on the on-board flight program for the European Ariane 4 launch vehicle. He is also a pianist and composer. More about Adam's music and space research - adamhibberd.com. He developed his Optimum Interplanetary Trajectory Software, in 2017 as a personal challenge to learn the MATLAB programming environment and language.