# 2014 $UN_{271}$ Spacecraft Missions

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Following his practical treatment of missions to interstellar objects. *Practicalities and Difficulties of a Mission to 'Oumuamua* in our last issue, Principium 33, Adam Hibberd here shows us how to reach another intriguing visitor to our solar system neighbourhood, C/2014 $UN_{271}$ (Bernardinelli-Bernstein). This is, on good authority, the largest comet we have yet seen. More about the Bernardinelli-Bernstein (BB) comet and earlier thoughts on a mission in *Mission to 2014 UN271 using OITS*, a News Feature by John Davies published earlier in the members area of the i4is website and now elsewhere in this issue of Principium.

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## 1 Flyby Missions

Flyby missions to $UN_{271}$, ie missions which approach and depart the objective without any significant correction to match velocities with the target, may be achieved by direct transfer from Earth to $UN_{271}$ or using a combination of powered or unpowered gravitational assists. Normally we seek to minimize fuel usage and so maximize the useful payload mass. This general aim, which would in practice have to be studied in detail on a specific mission-by-mission basis, can nevertheless be addressed in a generic sense by various methods and adopting different assumptions.

### 1.1 Direct Transfer

In this section we assume a direct transfer to $UN_{271}$ and that we wish to minimize the Hyperbolic Excess Speed at Earth, designated $V_\infty$. Generally, in preliminary mission design of the kind adopted here, the task is to minimize some metric of the interplanetary trajectory, usually $\Delta V$, the definition of this depending on the precise context. For the moment we shall assume $\Delta V = V_\infty$.

Figure 1 is a colour contour plot of direct trajectories, with two independent variables – on the x-axis are launch dates between 2020 and 2035 and on the y-axis are overall flight durations in years. The darker and bluer the colours, the lower the $\Delta V$. We see in this contour plot the yearly patterns resulting from the Earth occupying yearly sweet spots in its orbit with respect to $UN_{271}$, at which points the relative alignment of the two bodies are particularly propitious for missions.

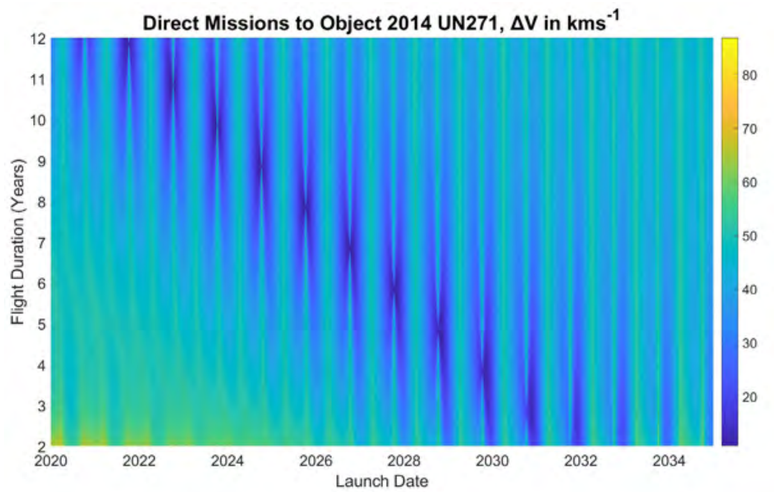



Figure 1: Direct trajectories, launch date versus flight duration, colour coded by $\Delta V$ see scale to right.

In Figure 2 we take Figure 1 results and filter out any trajectories for which the characteristic energy required at Earth, $C_3$ [1] is too large, specifically $C_3 > 400$ km²/s². (Note $C_3 = V_\infty^2$.)

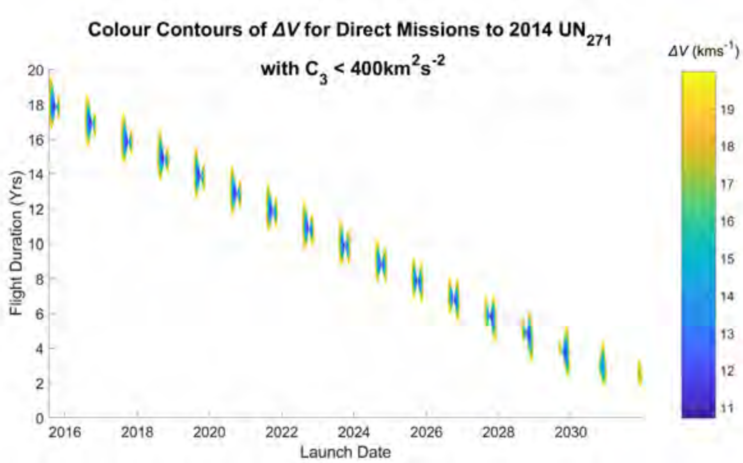



Figure 2: Direct trajectories showing feasible characteristic energies only, launch date versus flight duration, colour coded by $\Delta V$ see scale to right.

Observe in Figure 2 that there are limited areas of realistic viability for direct flyby missions and they tend to follow a diagonal arrangement on the graph. In fact as we progress from year to year, the feasible flight durations reduce by

[1] **Characteristic Energy**. Earth departure energy (km2/s2), equal to the square of the departure excess velocity - see *NASA/TM—2010-216764 Interplanetary Mission Design Handbook:Earth-to-Mars Mission Opportunities 2026 to 2045 Glenn Research Center 2010* (ntrs.nasa.gov/api/citations/20100037210/downloads/20100037210.pdf). For example, the SpaceX Falcon Heavy, can achieve the C3 of 50.5 km²/s²

almost precisely one year, from which we can infer that there is an optimal arrival date at the object $UN_{271}$. Perhaps as one might expect, this date corresponds to when the comet reaches its Ascending Node [1] with respect to the ecliptic plane, a point at which a spacecraft sent from Earth would ‘prefer’ to intercept $UN_{271}$, as it can then use Earth’s own planar velocity optimally to arrive at the target.

Numerical data on this is provided in Table 1 which gives a summary of the optimal launch scenarios displayed visually in Figure 2. Thus for launches between 2022 and 2027 inclusive, the optimal arrival date turns out to be 6 August 2033. For a launch date 2029 and beyond, there is simply insufficient time to intercept $UN_{271}$ at its Ascending Node and the corresponding ΔVs increase.

**Table 1** Optimal launch scenarios at feasible characteristic energies

| Launch Date | Arrival Date | Flight Duration (Days) | Flight Duration (Years) | ΔV at Earth (km/s) | $C_3$ at Earth ($km^2/s^2$) | Arrival Velocity (km/s) | Phase Angle (deg) [2] |
|---|---|---|---|---|---|---|---|
| 24 SEP 2022 | 06 AUG 2033 | 3969 | 10.87 | 10.77 | 115.92 | 13.74 | 114.89 |
| 27 SEP 2023 | 06 AUG 2033 | 3601 | 9.86 | 10.73 | 115.07 | 13.44 | 112.05 |
| 29 SEP 2024 | 06 AUG 2033 | 3233 | 8.85 | 10.70 | 114.43 | 13.13 | 108.47 |
| 02 OCT 2025 | 06 AUG 2033 | 2865 | 7.84 | 10.69 | 114.22 | 12.83 | 103.83 |
| 07 OCT 2026 | 06 AUG 2033 | 2495 | 6.83 | 10.72 | 114.87 | 12.57 | 97.64 |
| 13 OCT 2027 | 06 AUG 2033 | 2124 | 5.82 | 10.83 | 117.32 | 12.46 | 89.21 |
| 20 OCT 2028 | 07 AUG 2033 | 1752 | 4.80 | 11.13 | 123.85 | 12.77 | 77.66 |
| 31 OCT 2029 | 19 AUG 2033 | 1388 | 3.80 | 11.86 | 140.72 | 14.07 | 62.72 |
| 13 NOV 2030 | 25 OCT 2033 | 1077 | 2.95 | 13.63 | 185.82 | 17.02 | 47.38 |
| 26 NOV 2031 | 12 MAY 2034 | 898 | 2.46 | 17.06 | 290.97 | 20.46 | 37.01 |
| 03 DEC 2032 | 27 MAR 2035 | 844 | 2.31 | 21.71 | 471.15 | 22.56 | 31.31 |

## 1.2 Indirect Transfer

By contrast, an indirect transfer uses some combination of unpowered (without spacecraft thrust) or powered (with spacecraft thrust) Gravitational Assists (GAs) at one or more of the inner planets Venus, Earth and Mars, or the gas giant Jupiter.

### 1.2.1 Using Jupiter

By using Jupiter’s mass, a combined Jupiter GA and Jupiter Oberth manoeuvre (in other words a powered GA) can be attempted as a possible strategy by which overall mission ΔV can be reduced compared to the direct case (Section 1.1). In this context, we define here the overall mission ΔV as the sum of $V_\infty$ at Earth and the impulsive change in velocity required at perijove [3] to intercept and flyby $UN_{271}$.

We may inquire as to whether we can produce a colour contour plot for the mission here, ie using a Jupiter encounter, similar to that provided for the direct case in Section 1.1. The context here is more complicated in that there are two legs which combine to make the overall mission duration, the leg from Earth to Jupiter and that from Jupiter to $UN_{271}$.

[1] The **Ascending Node** is the point in an orbit at which the trajectory passes from below to above the reference plane. In this case the reference plane is the ecliptic, the plane of reference for the Solar System. Most planets orbit close to the ecliptic so we see the Solar System as more-or-less flat with just about all the angular momentum of the major bodies concentrated in the ecliptic. Comets from the Oort cloud, which is roughly spherical, are a major exception to this Solar System "traffic law"!

[2] **Phase Angle.** The angle between two lines subtended at the target body, the approach vector of the probe and the line between the Sun and the target body.

[3] **Perijove.** Closest approach to Jupiter. Corresponding to perihelion for the Sun and perigee for Earth.

However if we choose the optimal ratio of times for these legs (in terms of minimizing the previously defined ΔV) then we can construct a plot of the kind we are after. Thus refer to Figure 3.

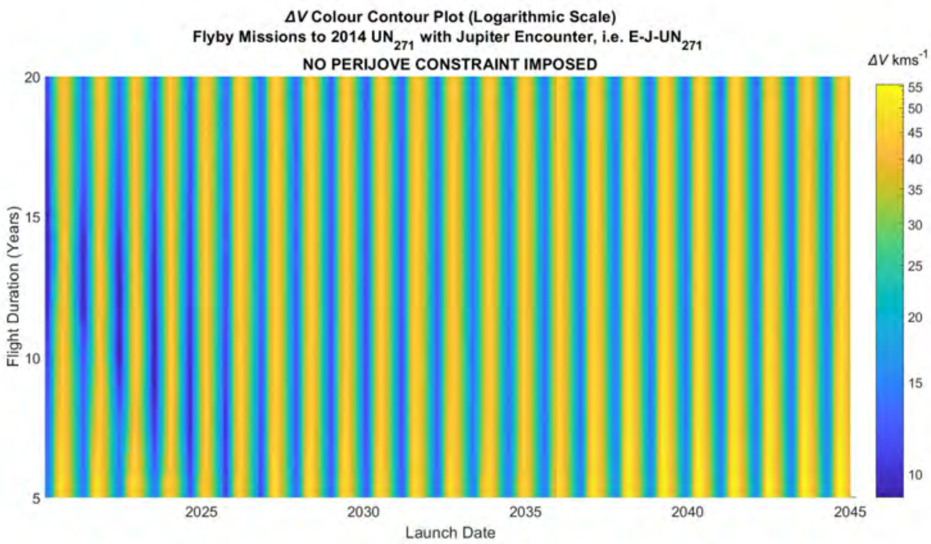



Figure 3: Indirect trajectories using Jupiter's mass with colour coded logarithmic ΔV scale.

Please note in Figure 3 the following:

1. There is no constraint on the minimum perijove altitude which the spacecraft can follow, thus this altitude may indeed be negative, obviously making the trajectory impossible to achieve in practice.

2. A logarithmic scale for ΔV is provided because of the large range of values this parameter can take.

3. There is no constraint on the perihelion distance along the interplanetary trajectory, ie from the Earth to Jupiter leg or the Jupiter to $UN_{271}$ leg.

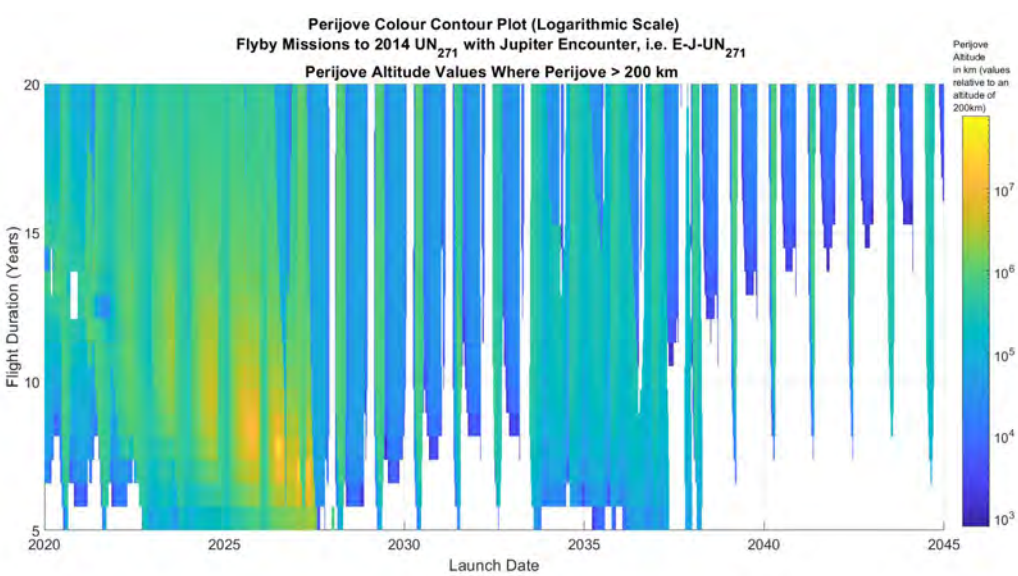



Figure 4: Avoiding bumping in to Jupiter! Colour codes vs reference altitude of 200km

To address first point (1), refer to Figure 4 which shows the perijove altitudes with respect to a reference altitude of 200 km. Again, due to the wide range of perijove altitudes required (a range of several orders of magnitude), a logarithmic scale is utilised. The white areas or gaps in this plot are where the perijove altitudes < 200 km have been removed.

Figure 5 takes the white areas in Figure 4 and removes them from Figure 3 and further neglects all trajectories for which the perihelion is < 0.5 AU. Figure 5 therefore represents feasible missions in terms of interplanetary trajectories and the orbital mechanics of the Jupiter encounter. Observe that there are two regions of general feasibility from around 2020 to 2027 and then again from 2034 to 2037. In both regions there exist gaps of infeasibility but more importantly, also regions of low ΔV.

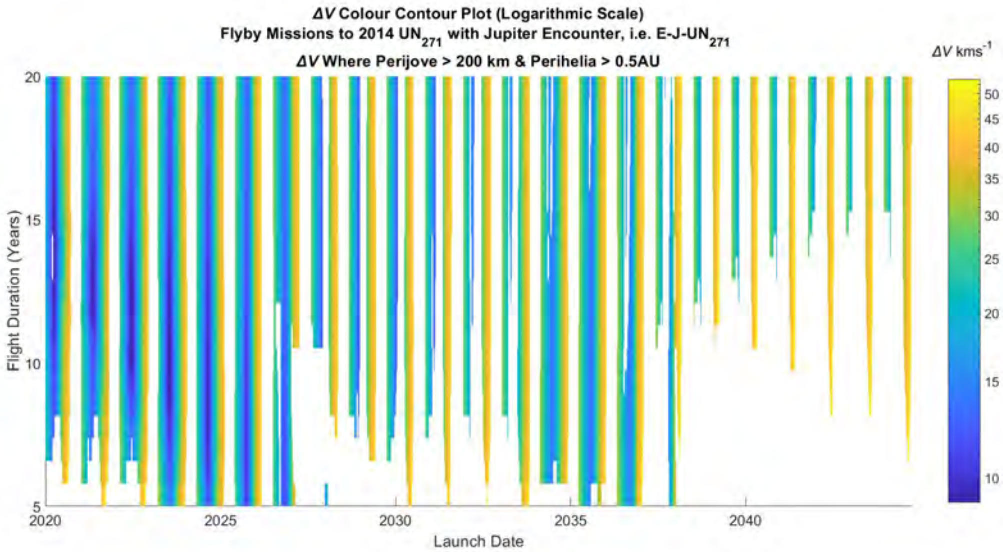



Figure 5: Feasible missions in terms of interplanetary trajectories and the orbital mechanics of the Jupiter encounter.

For an example trajectory involving launch in the year 2022, the minimal ΔV trajectory involves a launch on 21 JUN 2022, the ΔV is 8.9 km/s (all of which is $V_\infty$) and the arrival speed relative to $UN_{271}$ is 14.5 km/s, with a perijove altitude of 660,286 km. This can be compared to the New Horizons spacecraft where $V_\infty$ = 12.6 km/s, perijove altitude was 2,300,000 km and the arrival speed was 13.8 km/s.

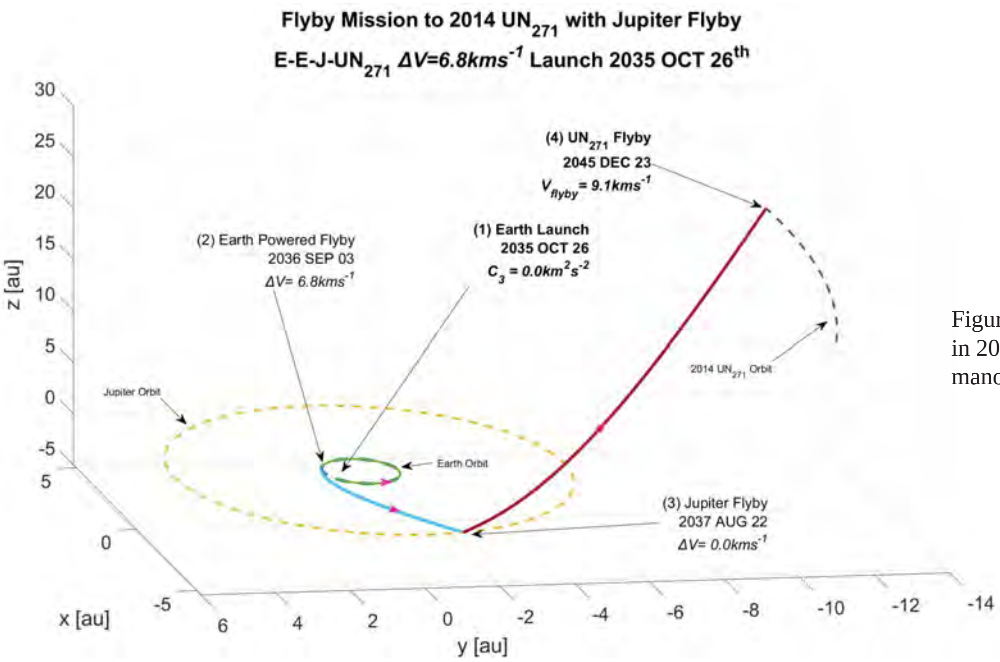



Figure 6: trajectory for a launch in 2036 with one year leveraging manoeuvre.

If we home in on the second of these intervals, 2034 to 2037, specifically a launch in 2036 and furthermore precede the trajectory from Earth to Jupiter by a one year leveraging manoeuvre with a 1:1 Earth resonance [1] we find the trajectory shown in Figure 6. This leveraging has the benefit of significantly reducing the $C_3$ at Earth launch, in fact to zero.

In addition it would seem the overall ΔV is reduced, however this is partly as a result of the definition of ΔV we have used. Clearly a $C_3 = 0.0$ km²/s² ignores the contribution to the ΔV required by the launch vehicle in question.

[1] Orbital resonance - hosting.astro.cornell.edu/academics/courses/astro6570/orbital_resonances.pdf

### 1.2.2 Using the Inner Planets

Various combinations of inner planets were tried and there can be no guarantee with OITS as to whether a global optimum is reached, in terms of both (a) finding an optimal solution trajectory in a user-specified sequence of planetary encounters, and (b) finding the globally optimum sequence of encounters.

In the case of (b), it is the responsibility of the user to specify to OITS the precise combination and sequence of encounters to adopt and it is therefore a question of trying many such combinations, running OITS many times, and concentrating on those which are the best in terms of minimizing ΔV. Table 2 provides a summary of the results. Note a preceding one year leveraging manoeuvre, with a launch one year before the optimal launch dates provided would generally serve to reduce the overall ΔV for the trajectories and also to reduce the $C_3$ needed at Earth to 0.0 $km^2/s^2$.

The lowest ΔV of 5.54 km/s in Table 2 corresponds to the sequence E-Vr-V-E-$UN_{271}$ (with the Venus-Venus segment incorporating a Deep Space Manoeuvre at a 2:1 resonance with Venus, ie at 1.57 AU). The launch is 2028 MAR 10, and arrival at $UN_{271}$ is on 2033 OCT 18.

Table 2. Minimum ΔV trajectories from multiple OITS runs.

| Trajectory (r=resonance) | Aphelia for Resonances and heliocentric distance of DSM (AU) | Launch Date | Arrival Date | Total ΔV (km/s) | $C_3$ ($km^2/s^2$) | Approach Velocity (km/s) | Arrival Helio-centric Distance (AU) | In-flight ΔV (km/s) | Phase Angle (deg) |
|---|---|---|---|---|---|---|---|---|---|
| E-Vr-V-E-$UN_{271}$ | 1.57 | 2028 MAR 10 | 2033 OCT 18 | 5.53 | 10.35 | 13.5 | 12.11 | 2.32 | 114.89 |
| E-V-Er-E-$UN_{271}$ | 2.20 | 2026 AUG 06 | 2033 SEP 09 | 6.42 | 12.6 | 14.01 | 12.02 | 2.87 | 116.01 |
| E-Vr-Vr-V-$UN_{271}$ | 1.57, 2.92 | 2025 JAN 07 | 2033 NOV 12 | 6.50 | 13.7 | 12.5 | 12.16 | 2.8 | 103.90 |
| E-Vr-Vr-V-$UN_{271}$ | 1.57, 2.28 | 2025 JAN 11 | 2033 NOV 11 | 7.04 | 13.63 | 12.2 | 12.16 | 3.34 | 95.68 |
| E-Vr-V-M-V-$UN_{271}$ | 1.57 | 2025 FEB 04 | 2033 OCT 15 | 7.23 | 13.9 | 11.97 | 12.1 | 3.5 | 89.60 |
| E-Vr-V-$UN_{271}$ | 2.28 | 2025 MAR 03 | 2033 NOV 11 | 7.31 | 15.8 | 12.23 | 12.16 | 3.34 | 83.14 |
| E-Vr-V-M-DSM-V-$UN_{271}$ | 1.57, DSM = 2.28 | 2025 FEB 08 | 2033 NOV 25 | 7.52 | 14.34 | 11.97 | 12.19 | 3.73 | 95.13 |
| E-Vr-V-$UN_{271}$ | 1.57 | 2025 MAR 12 | 2033 NOV 03 | 7.81 | 17.38 | 12.38 | 12.16 | 3.64 | 101.32 |
| E-M-E-$UN_{271}$ | N/A | 2026 NOV 26 | 2033 AUG 07 | 7.83 | 30.48 | 12.65 | 11.9 | 2.31 | 102.16 |
| E-Vr-V-M-DSM-V-$UN_{271}$ | 1.57, DSM = 2.92 | 2025 MAR 18 | 2033 NOV 27 | 9.86 | 35.26 | 12.57 | 12.19 | 3.92 | 103.17 |
| E-Vr-V-E-DSM-V-$UN_{271}$ | 1.57, DSM = 2.28 | 2025 JAN 02 | 2033 OCT 03 | 10.32 | 8.4 | 12.22 | 12.07 | 7.42 | 96.96 |

## 2 Rendezvous Missions

Unlike flyby missions, covered in Section 1, rendezvous missions involve an application of thrust as the target is approached to match velocities with it.

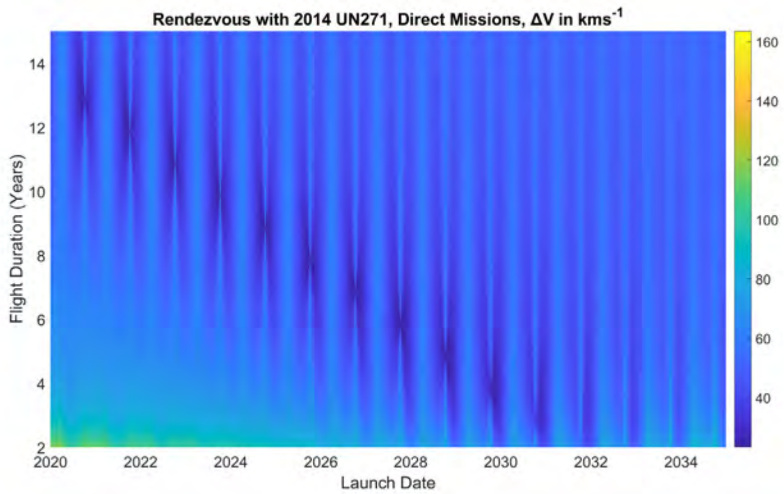



Figure 7: Direct Transfer, launch date versus flight duration,. Adding ΔV at the target to achieve rendezvous.

Colour coded by ΔV see scale to right.The darker and bluer the colours, the lower the ΔV.

Note ΔV always exceeds 20.0 km/s.

Compare Figure 1 in Section 1.1 which shows the flyby case.

### 2.1 Direct Transfer

A colour contour plot is provided in Figure 7 which is analogous to Figure 1 in Section 1.1, but in addition to the $V_\infty$ needed at Earth, has an extra ΔV at the target, $UN_{271}$, in order to rendezvous with it. The main conclusion which can be drawn from this, is that the total ΔV required for this is much larger, and in fact always exceeds 20.0 km/s.

### 2.2 Indirect Transfer

### 2.2.1 Using Jupiter

Analogous contour plots to those used for the flyby case provided in Section 1.2.1 can be constructed for the rendezvous case and are provided in Figures 8 to 10.

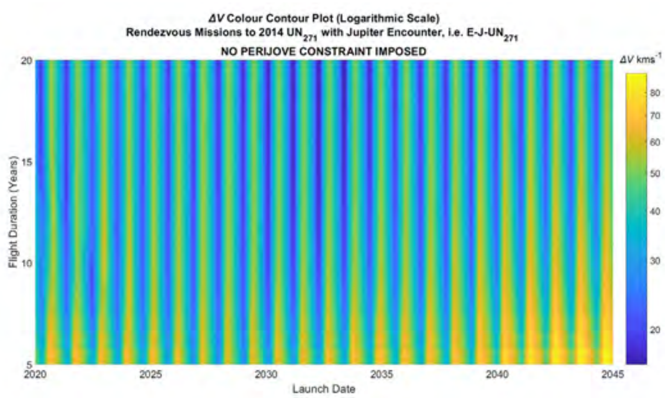



Figure 8: Theoretical optimal launch dates for a rendezvous mission with a single Jupiter encounter.

From Figure 8, we can observe that the theoretical optimal launch dates for a rendezvous mission with a single Jupiter encounter (without filtering out negative perijove altitudes) are around 2030 to 2034 and with flight durations around 14-15 years.

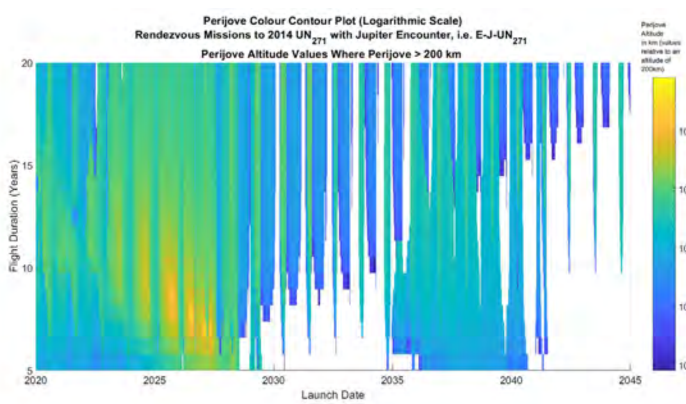



Figure 9: Rendezvous mission with a single Jupiter encounter and limited perijove.

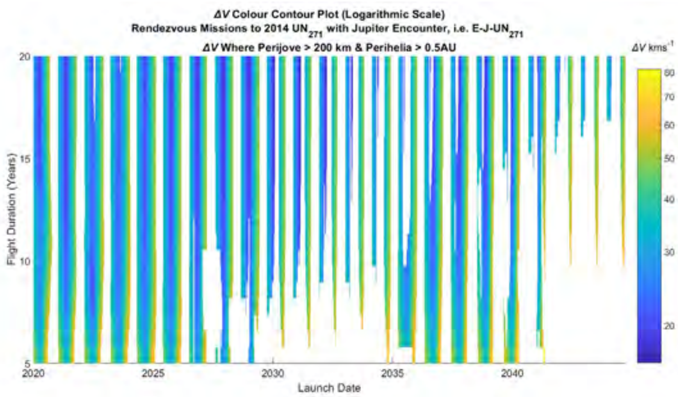
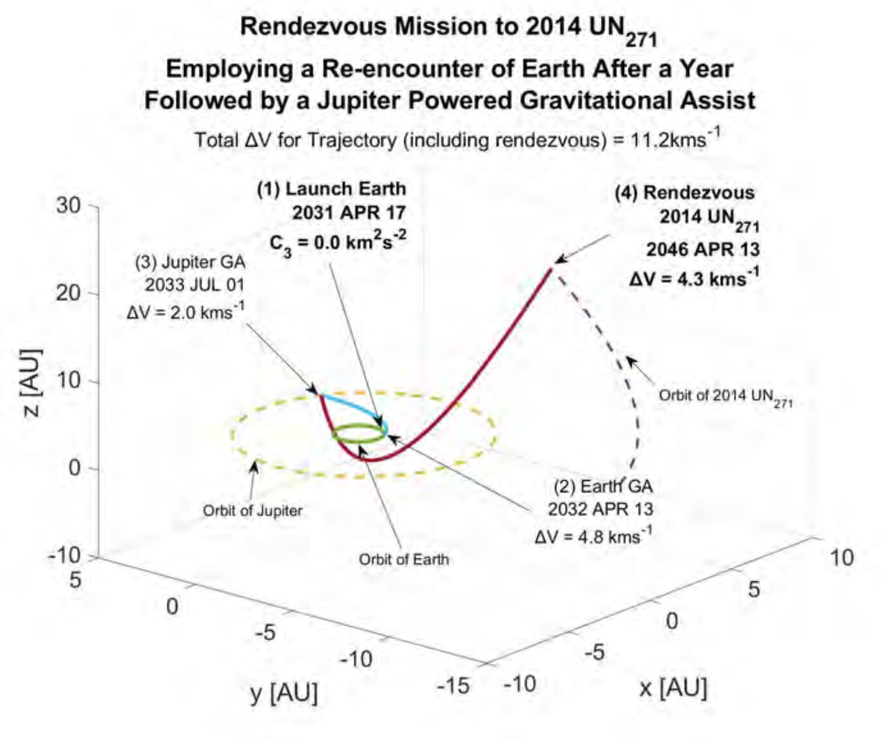



Figure 10:. Feasible trajectories for rendezvous via Jupiter with limited perihelion and perijove.

From Figure 10 we can see that when we remove negative perijove altitudes and low perihelia, most of the landscape for the region 2030 to 2034 is removed and is in fact infeasible.

However there are also regions of feasibility and to take a case in point, we assume a launch in 2032 and flight duration 14 years from Figure 10 and precede it by an Earth leveraging manoeuvre with 1:1 resonance (to make the launch one year earlier) and we get the trajectory shown in Figure 11.

Figure 11: Selected trajectory for launch in 2032 and flight duration 14 years.




Note that the optimal Rendezvous point is not in the ecliptic plane, contrary to what was observed for direct missions.

The reasons for this are:

- An intercept with $UN_{271}$ in the ecliptic plane would inevitably mean that the angle between approach velocity of the spacecraft and the velocity of $UN_{271}$ would be around 90°. This is because the orbital inclination of $UN_{271}$ is just over 90° which means on crossing the ecliptic its velocity will primarily be along the heliocentric z-axis direction.
- The magnitude of the velocity of $UN_{271}$ reduces as it becomes further displaced from the ecliptic plane making the change in velocity of the spacecraft more manageable.

## About The Author

Adam Hibberd was educated at a state school, Stoke Park Comprehensive School and Community College, in Coventry and attended the University of Keele, gaining a joint honours degree in physics and maths. He worked in the '90s as a software engineer on the on-board flight program for the European Ariane 4 launch vehicle - including the production, maintenance, real-time testing and post-flight analysis, his expertise being the guidance algorithm. He is also a pianist and composer and, as a member of musical trio 'Superheroes Dream', produced a vinyl under the Coventry Tin Angel Record Label. More about *Adam's Music and Space Research* - adamhibberd.com.

Adam developed his Optimum Interplanetary Trajectory Software, 'OITS' in 2017 as a personal challenge to learn the MATLAB programming environment and language. He then used it to investigate missions to interstellar objects (the work being published in Acta Astronautica) and is now a research volunteer for i4is.