

How to reach Interstellar Visitors

Optimum Interplanetary Trajectory Software

Adam Hibberd

When the first interstellar object to be discovered in our solar system, 1I/‘Oumuamua, was spotted by the team at the Pan-STARRS telescope in Hawaii, a team of experts from the Initiative and Institute for Interstellar Studies came together to assess the feasibility of intercepting this messenger from the galaxy. Some time before this, Freelance Software Engineer Adam Hibberd was looking into general solutions for interplanetary trajectories and had developed his Optimum Interplanetary Trajectory Software (OITS) when he became aware of the i4is work and contacted Andreas Hein. The rest, as they say, is history. Here Adam gives his account of what happened and how he and the i4is Project Lyra team pioneered the work of mission planning to reach both 1I/‘Oumuamua and have now extended it to the later 2I/Borisov comet.

Adam begins with a brief autobiographical background and how he contacted Andreas Hein, going on to detail the mathematical methods he used to deliver the Project Lyra team results.

I am educated to degree level in physics and maths and in 1990, after leaving university, I was hired as a software engineer by a company in Camberley, Surrey called EASAMS Ltd. I was employed in the Ariane 4 Project which had responsibility for development, production, real-time testing and post-flight analysis of the on-board flight software for the European Ariane 4 satellite launch vehicle.

Ultimately I became a specialist in Ariane 4 Guidance which required an understanding of Optimum Launcher Ascent Trajectory to Orbit Software. This is where I picked up an interest and enthusiasm in optimum trajectory theory and orbital mechanics.

Since then I have worked for various companies as a software engineer, however in 2004 I changed my career path entirely and became a composer/musician. (This has always interested me – in fact as a child I played and composed on the piano.) As a part of the musical group Superheroes Dream, we produced a vinyl under the Coventry Tin Angel record label.

In 2017 I decided to pick up a computer keyboard again and try to get to grips with MATLAB which is a programming language which has always intrigued me. In order to do this I set myself the challenge of developing a tool for calculating optimum interplanetary trajectories. I decided to approach it with very little reference to the scientific literature, so I could view the problem with an open and objective point of reference. Having derived the theory, I then subsequently implemented the equations using MATLAB into a software application which I called ‘OITS’ – that’s ‘Optimum Interplanetary Trajectory Software’.

Naturally OITS would need accurate position and velocity calculation for the celestial bodies. My logic here was that NASA would have developed their own software to do precisely this and indeed they had – it’s called SPICE (<https://naif.jpl.nasa.gov/naif/toolkit.html>) and fortuitously, there is a MATLAB version of this toolkit. Thus rather than re-inventing the wheel, I decided to exploit this software and link it in with my OITS tool, as third party software.

As will be explained later, the theory behind OITS also requires a global ‘Non-Linear Programming’, NLP solver. Having tried various options, I discovered ‘NOMAD’ (<https://www.gerad.ca/nomad/>) to be extremely good for the problem in hand.

I knew I was onto something when OITS started solving and reproducing historic missions such as Voyager 2, Cassini and Mars Insight Lander to excellent accuracy.

When the first interstellar object, ‘Oumuamua was discovered in 2017, I had largely developed my software so I decided to investigate interplanetary missions to this object. With a bit of further research online I found that Project Lyra of i4is had been working on precisely the same problem as I had – missions to ‘Oumuamua. I contacted Andreas Hein with my results and so started a fruitful relationship with i4is.

In the end, we produced two papers on the subject of missions to ‘Oumuamua, the first of which was published by the peer-reviewed journal, 'Acta Astronautica' (<https://www.sciencedirect.com/science/article/abs/pii/S0094576518317004>), the second of which I was largely responsible for the research and has been published online (<https://arxiv.org/abs/1902.04935>).

The reason for the success of OITS in the context of the Project Lyra research, is partly because of the incorporation of the notion of ‘Intermediate Points’ (IP). Essentially an IP is a massless and static point in space whose distance from the centre of the Solar System is user-specified but whose polar angles (so heliocentric longitude and latitude) are allowed to be optimised by the NLP software. Such a point can be used to model something known as a ‘DSM’ or ‘Deep Space Manoeuvre’. For a spacecraft to get to ‘Oumuamua, for example, it needs to do a ‘Solar Oberth’, where it approaches very close to the Sun (within a few solar radii) and then a burn is applied at this perihelion point. Such a manoeuvre can easily be modelled by OITS using an IP and so viable trajectories using this technique can be investigated. An example of such a trajectory is provided below. This 3D plot was generated by OITS and manipulated by me using the MATLAB Integrated Development Environment to get it into a presentable form.

I developed an animation option for OITS and an animation for the above trajectory can be found here:

<https://drive.google.com/open?id=1Pgcdl4kuz7rxSJ30PDkafvohbg2G63P8>

With the discovery of the second interstellar object, Borisov, we managed to also produce a paper very quickly and take advantage of all the media attention it was receiving (<https://arxiv.org/abs/1909.06348>).

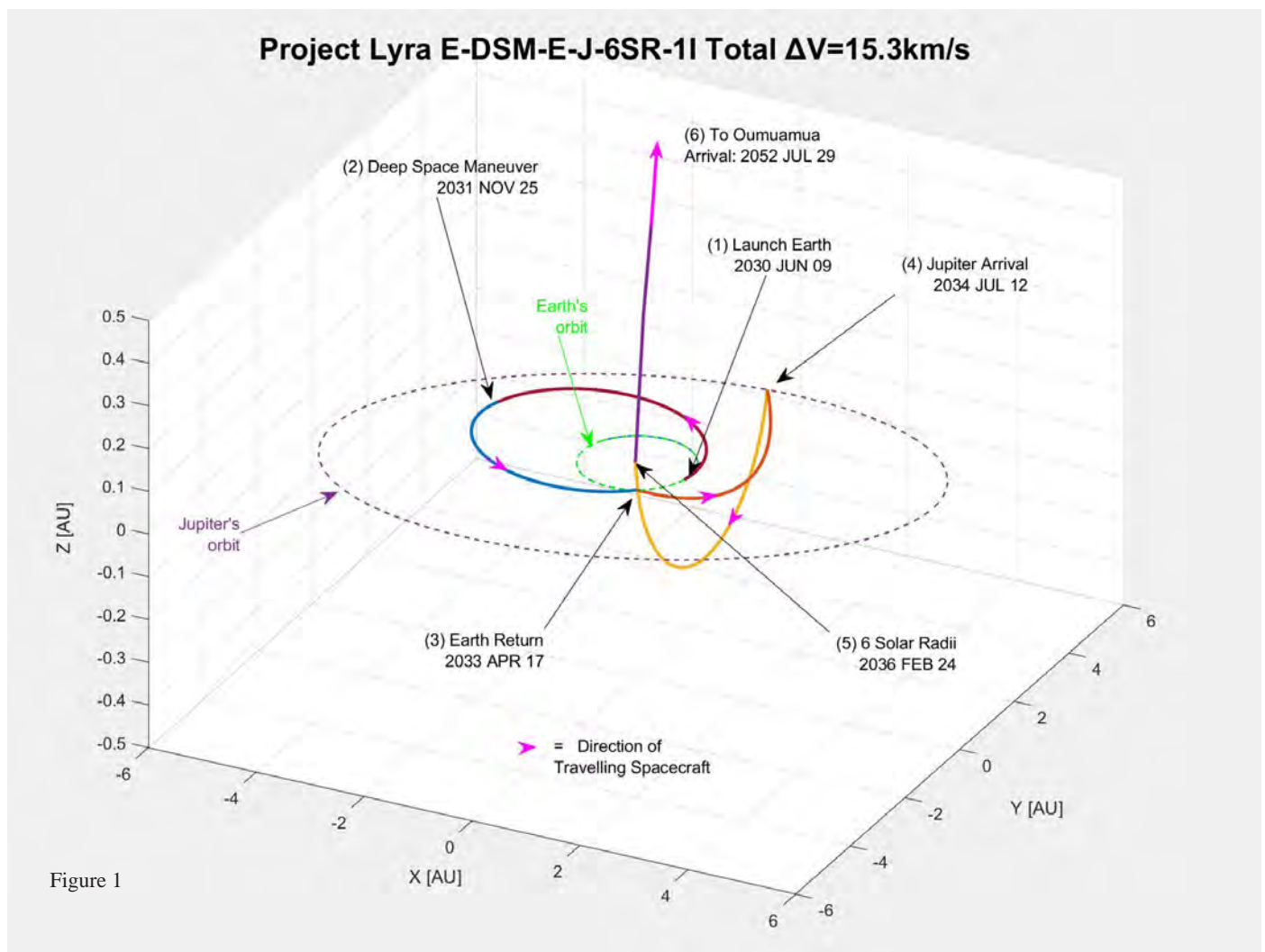


Figure 1

General Principles of Optimum Interplanetary Trajectory Software (OITS)

The following is not intended to be an accurate definition of the theory behind OITS and the precise algorithm employed by OITS differs in various respects to that elaborated here. However, you can get a good idea of the general principles behind it.

Figure 2. Let us assume there are two stationary bodies A and B and that a travelling spacecraft has to be at A at time t_A and arrive later at B at time t_B , where $t_B > t_A$.

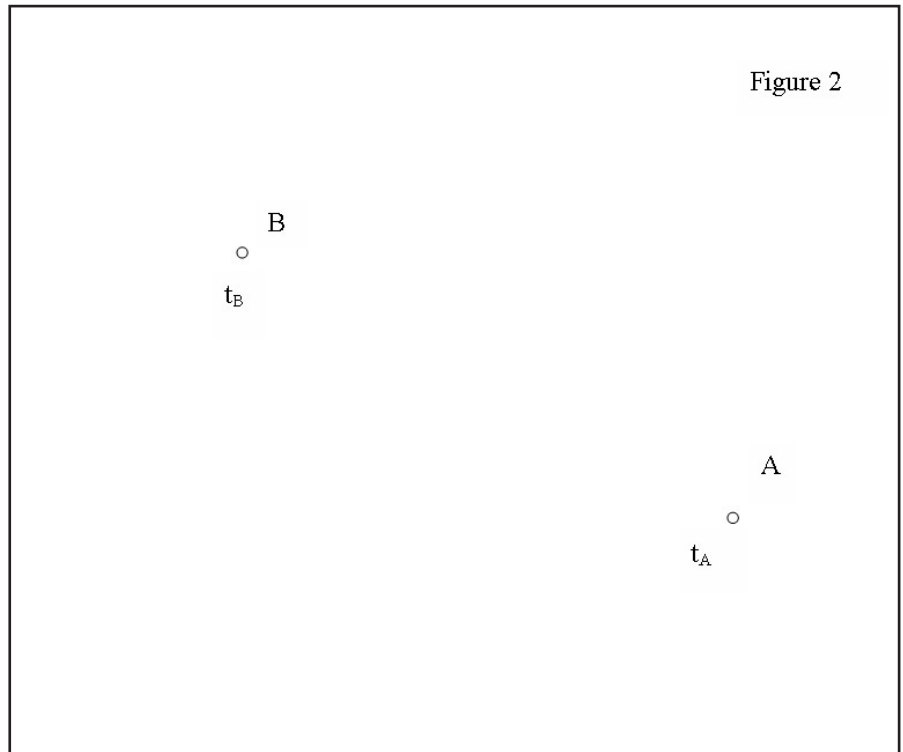


Figure 3. Furthermore we know the displacement between A and B is ΔR . We can ask what is the velocity we need at A to get to B?

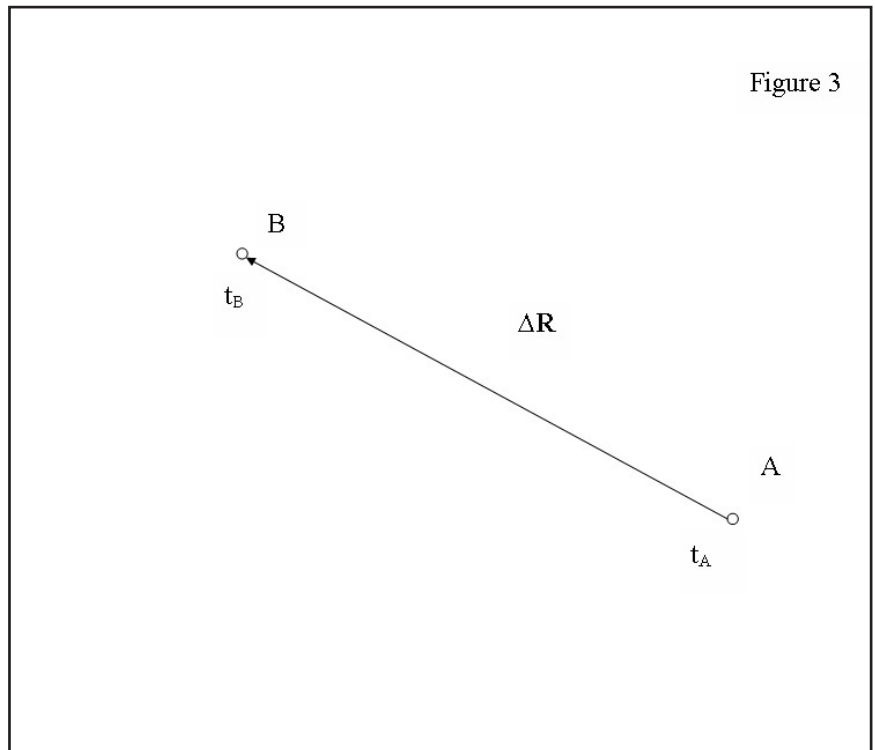


Figure 4. The answer is we need a velocity at A of \mathbf{V}_{AB} given by $\mathbf{V}_{AB} = \Delta\mathbf{R}/(t_B - t_A)$.

But what if A and B are moving themselves? Take a look at Figure 5.

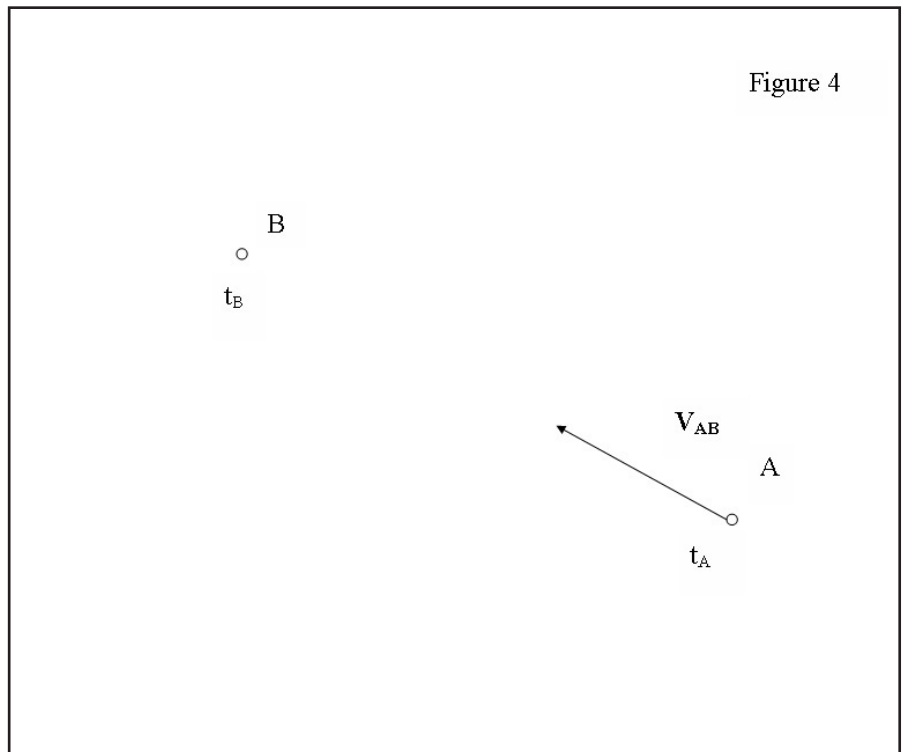


Figure 4

Figure 5. So we assume A and B are travelling in space with respective velocities \mathbf{V}_A and \mathbf{V}_B . Also assume that our spacecraft originates from body A, so initially has the same velocity, \mathbf{V}_A .

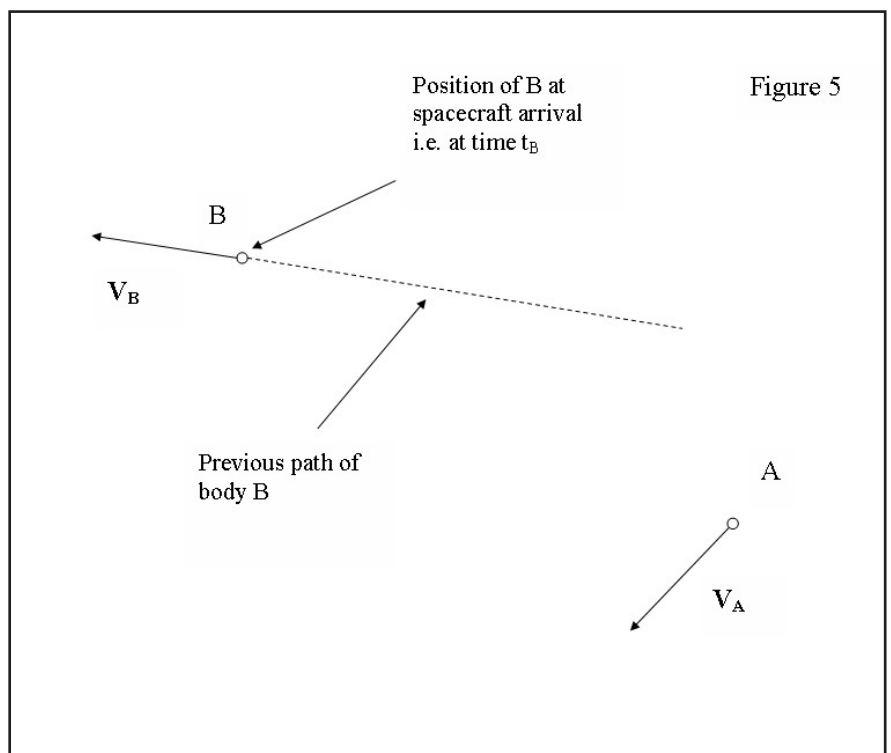
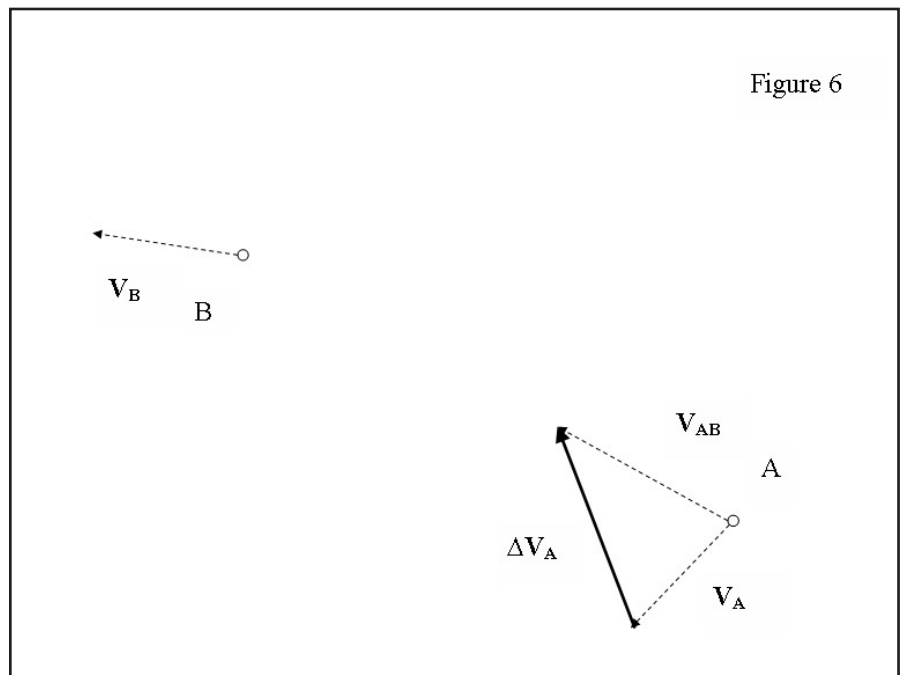
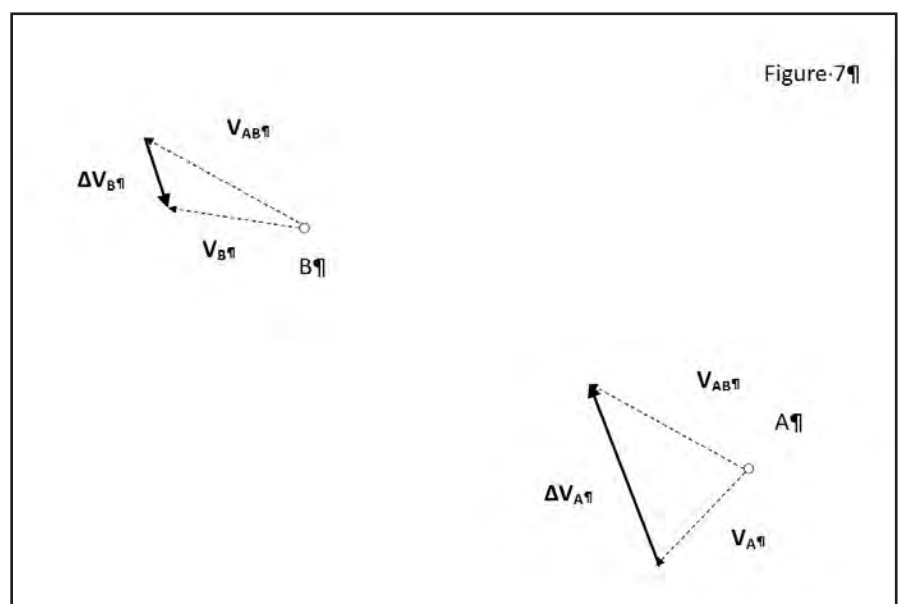


Figure 5

Then as we can see from Figure 6, the spacecraft now needs to apply a change in velocity ΔV_A in order to arrive at the intended target B at time t_B .



However in Figure 6, once it arrives at B it will simply flyby B. So this is an 'intercept'. What if we wish to stay with B after arrival? Then we also need to apply a ' ΔV ' at B, ΔV_B , as can be seen in Figure 7. In other words a 'rendezvous'.



The general idea behind OITS, is that we need to find the times t_A and t_B such that the 'effort' needed to get from A to B is minimised. This 'effort' is quantified as follows:

For Intercept:

Find t_A and t_B such that the magnitude of ΔV_A is minimised,
ie minimise $|\Delta V_A|$

For Rendezvous:

Find t_A and t_B such that the sum of the magnitudes ΔV_A and ΔV_B is minimised,
ie minimise $|\Delta V_A| + |\Delta V_B|$

But we have ignored the gravitational attraction of the Sun. In fact, this will ‘bend’ the velocity V_{AB} , so that the s/c will be sent off-course. Refer Figure 8.

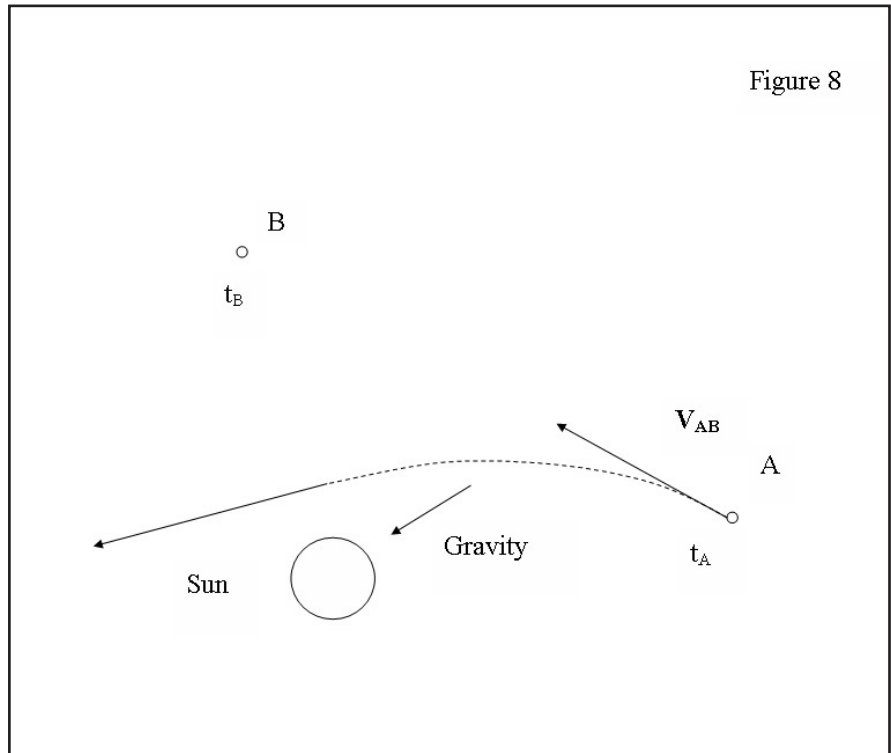
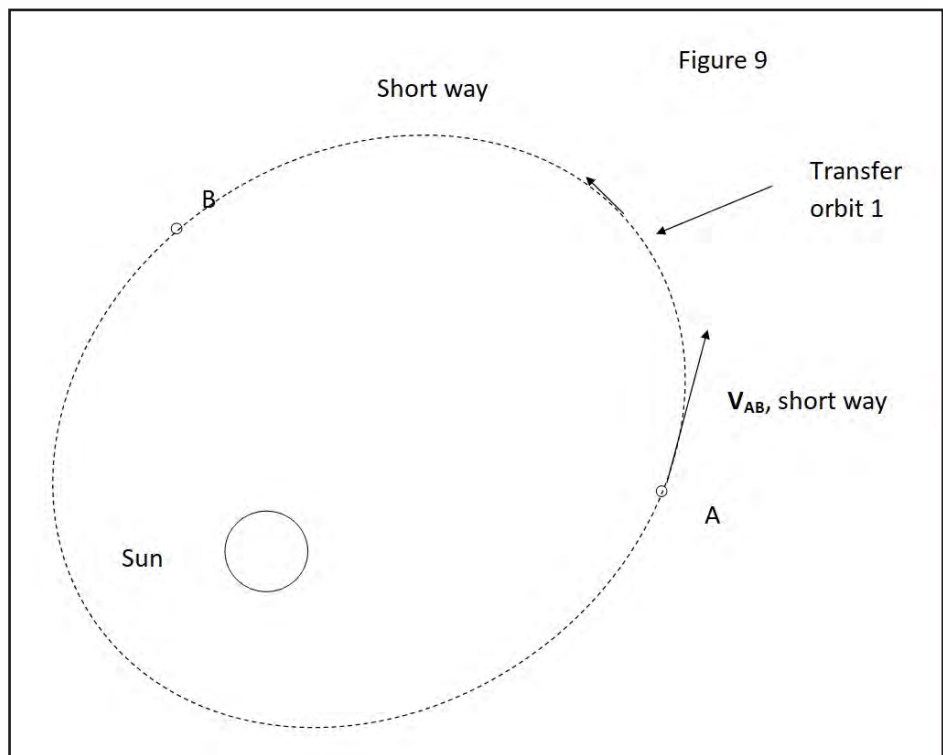
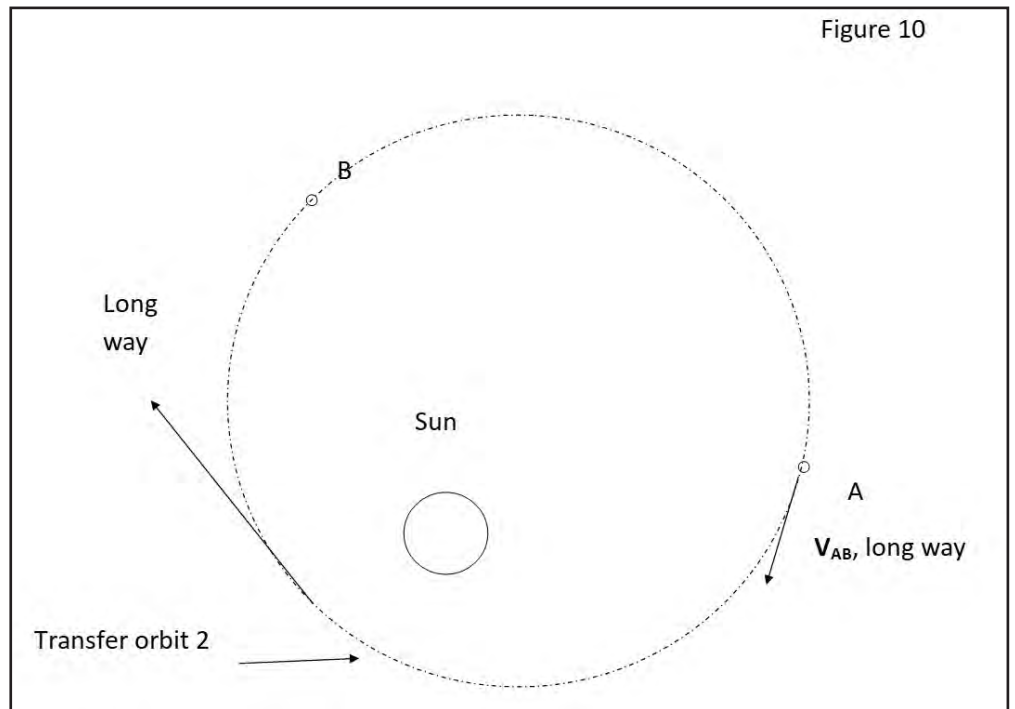


Figure 9 shows the solution to this problem.

In the presence of gravity of the Sun, there are actually two ways of travelling from A to B, ‘short way’ and ‘long way’.

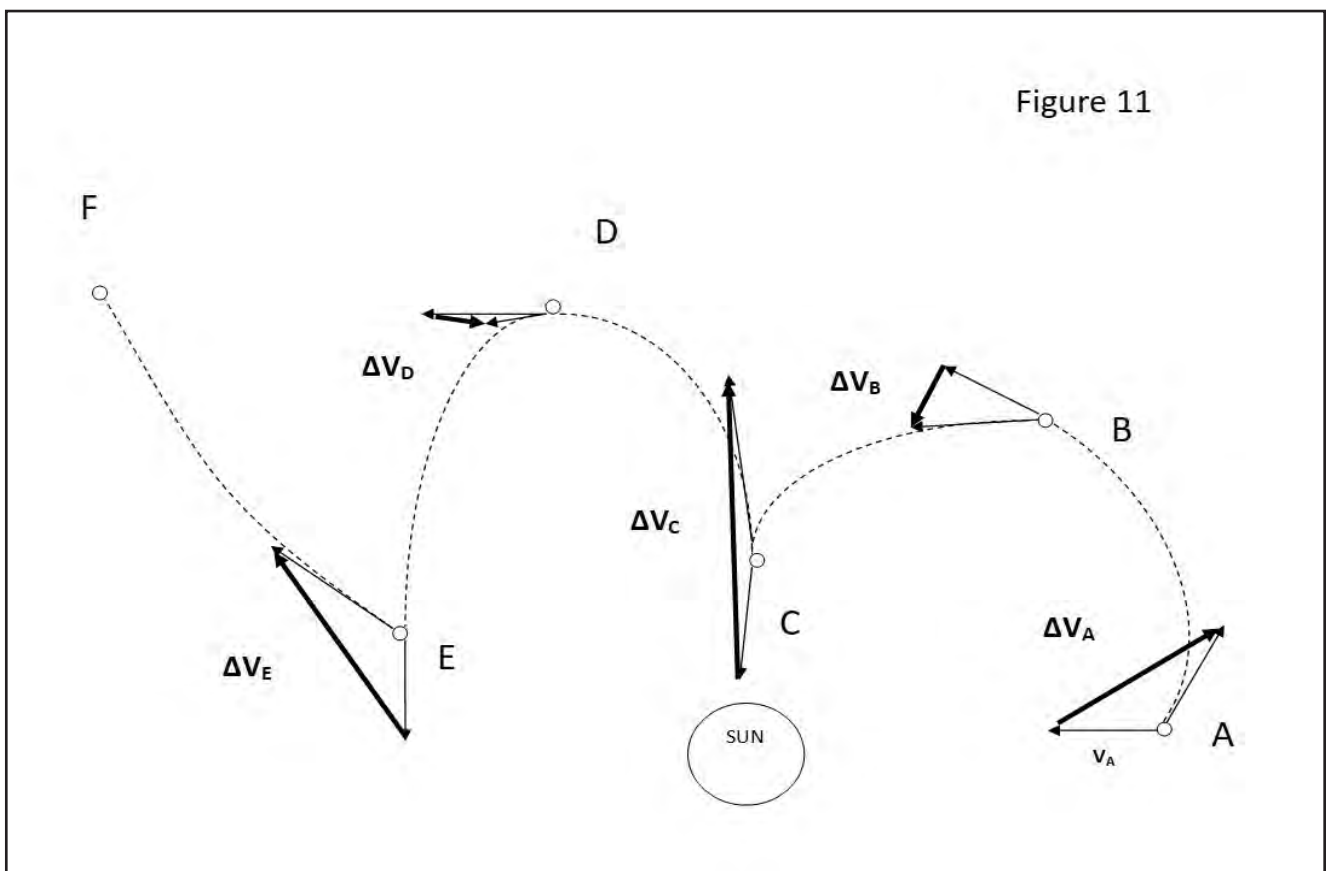


See Figure 10 for long way.



The solution to finding the two transfer orbits, short way and long way (see Figures 9 & 10), given departure time and arrival time and corresponding positions at departure and arrival, is a well-known problem of astrodynamics, known as the Lambert problem, and a possible numerical method of solution is provided in ‘Fundamentals of Astrodynamics’ (Bate, Mueller and White). The so-called ‘Universal Variable Formulation’.

Figure 11, introduces the idea that there may be more than 2 bodies, the example given is for 6 bodies, labelled A, B, C, D, E and F.



So what OITS tries to do is find the times $t_A, t_B, t_C, t_D, t_E,$ and t_F such that the cumulative ΔV_{TOT} (total deltaV - en.wikipedia.org/wiki/Delta-v_budget) is a minimum. ΔV_{TOT} is given by:

$$\Delta V_{TOT} = |\Delta V_A| + |\Delta V_B| + |\Delta V_C| + |\Delta V_D| + |\Delta V_E| + |\Delta V_F|$$

Given the known orbital paths of A, B, C, D, E & F around the Sun, ΔV_{TOT} is in fact only a function of the times $t_A, t_B, t_C, t_D, t_E,$ and t_F .

In the general case, let there be 'Nbody' total number of bodies. From Figures 9 & 10, we can deduce there are in fact $2^{(Nbody-1)}$ ways of getting from body number 1 to the final body, ie there are this many permutations of short ways and long ways. Of all the possible permutations, we choose the one which minimises ΔV_{TOT} .

Problem Statement

So our problem can be stated as follows:

PROBLEM: Find times $t_A, t_B, t_C, t_D, t_E,$ and t_F such that $\Delta V_{TOT} = f(t_A, t_B, t_C, t_D, t_E, t_F)$ is a minimum.

The problem stated above is a 'Non-Linear Programming' problem, ie NLP. There may be some constraint functions also. There are various NLP solvers available on the internet which can solve such a problem. The function, f , is treated as a black-box and is user defined. The NLP then repeatedly feeds this black-box the input variables (in this case $t_1, t_2, t_3 \dots t_{Nbody}$) and the user-defined function, f , is executed. It is the purpose of the NLP to so change the input variables iteratively until the global minimum of f is found, subject to satisfying all the constraints.

Given a sequence of celestial bodies $i=1,2,3\dots Nbody$, and a sequence of times $t_i, i=1,2,3\dots Nbody$, the corresponding positions and velocities of each of the celestial bodies need to be calculated. As well as holding a massive database of celestial bodies, the NASA SPICE toolkit also allows accurate determination of their positions and velocities (the ephemerides - en.wikipedia.org/wiki/Ephemeris) and can be linked in with the MATLAB software. Having so calculated the ephemerides, the Universal Variable Formulation can then be applied to calculate the value of ΔV_{TOT} , as previously explained. The NLP software can then be utilised to find the global minimum. I used a global NLP tool called NOMAD (editors note: see Adam's opening remarks and <https://www.gerad.ca/nomad/>).

Note that all of the variables $t_i, i=1,2,3\dots Nbody$ are usually restricted to user-defined intervals, ie a solution is found subject to bounds on these variables. Also note that the celestial bodies $i=1,2,3\dots Nbody$, have masses and hence gravitational attractions of their own and in fact OITS incorporates the encounter dynamics of the spacecraft with each of these bodies. Thus in actuality the calculation of ΔV_{TOT} used by OITS is not precisely as described above.

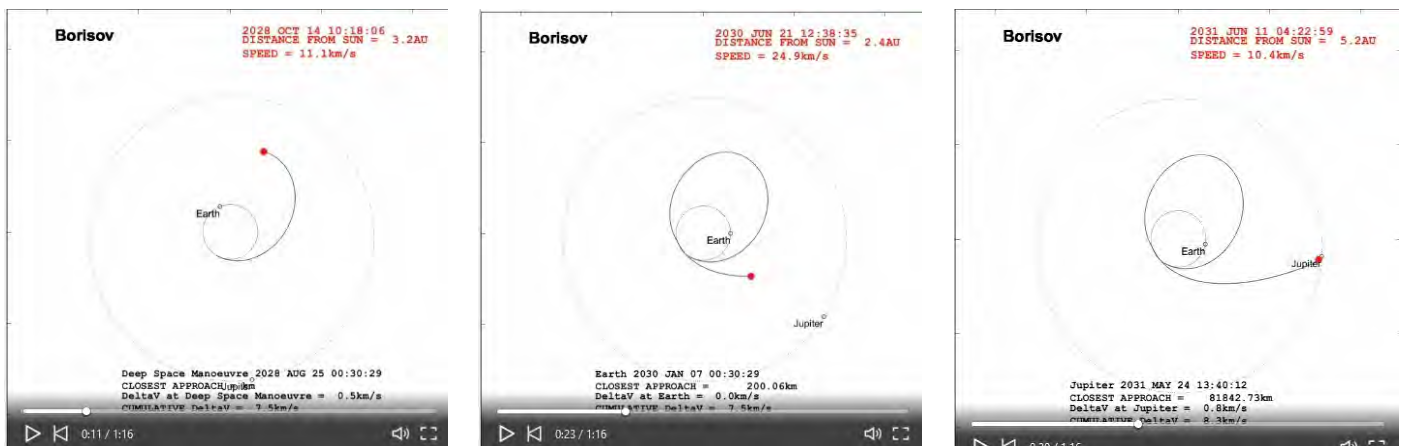
About the Author

Adam Hibberd has already told his own story but a few additional notes may be of interest.

Adam has a Joint Honours Bachelor's Degree in Physics and Mathematics from Keele University, UK. His earlier education was at a state comprehensive school in Coventry in the English Midlands.

To see some of his most recent work in animated form look at www.linkedin.com/in/adam-hibberd-b73339136/detail/recent-activity/ showing a dramatic trajectory from Earth 2027, an Earth slingshot, a Jupiter slingshot, a precipitous dive into the Sun, an Oberth perihelion burn and an intercept with comet Borisov in 2051, when your editor will be 105 years old!

Here are some snapshots -



The probe leaves Earth on an elliptical trajectory, comes back to Earth and is slingshotted to Jupiter...



A Jupiter slingshot gives it a Sun-grazing trajectory to receive best Oberth effect at perihelion so that (with a considerable change of scale) the probe overtakes comet Borisov.