Politecnico di Milano

Prova finale: Introduzione all’analisi di missioni spaziali
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# Elaborato n. B17

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## 1. Introduction

The purpose of this report is to analyse different strategies for the transfer of a satellite between two given orbits.
The coordinates of the initial point are expressed towards a cartesian reference system which is earth inertial centred, while the coordinates of the final point are assigned by the orbital parameters.
Our data and considerations are based on several hypothesis:

- Earth is the only body which exerts a gravitational force on the satellite (two-body problem, lecture 02, slide 8)
- All the analysed orbits have the same focus, which is the Earth (confocal orbits)
- All the manoeuvres are impulsive, due to the instantaneous variation of moment of momentum. The main effect is the variation of the vector velocity (lecture 07, slide 3).

We are going to expose the most significant strategies, establishing the optimal one in terms of minimum transfer time and minimum amount of fuel required, remembering that the quantity of fuel is directly connected with the magnitude of the variation of velocity.

## 2. Initial orbit characterisation

### 2.1. Determination of initial orbital parameters

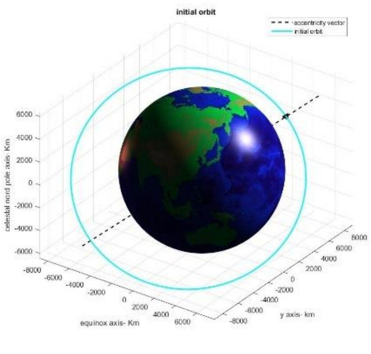
| | X | Y | Z | Magnitude |
|---|---|---|---|---|
| **r [km]** | -7976.6789 | -6009.0790 | -93.1888 | 9.9872e+3 |
| **v [km/s]** | 2.2840 | -3.7980 | -3.9860 | 5.9607 |

| **a [km]** Semi – major axis | **e[-]** eccentricity | **i [deg]** orbital inclination | **ω[deg]** argument of periapsis | **Ω [deg]** RAAN | **θ [deg]** true anomaly |
|---|---|---|---|---|---|
| 8.9993e+3 | 0.1377 | 42.0938 | 33.3829 | 36.400 | 147.4147 |

### 2.2. Considerations and other important data

| **E [km²/s²]** Orbital specific energy | **Shape** of orbit | **T [h]** Revolution time | **p [km]** Semi-latus rectum | **Type** of orbit |
|---|---|---|---|---|
| -22.1461 | elliptical | 2.3601 | 8.8288e+3 | Direct |
| **$r_a$ [km]** apocenter radius | **$r_p$ [km]** pericenter radius | **$v_a$ [km/s]** apocenter velocity | **$v_p$ [km/s]** pericenter velocity | |
| 1.0238e+4 | 7.7605e+3 | 5.7942 | 7.6442 | |

### 2.3. Graphical representation of the initial orbit



## 3. Final orbit characterisation

### 3.1. Determination of final position and velocity from assigned final orbital parameters

| **a [km]** Semi- major axis | **e [-]** eccentricity | **i [deg]** orbital inclination | **ω [deg]** argument of periapsis | **Ω [deg]** RAAN | **θ [deg]** true anomaly |
|---|---|---|---|---|---|
| 1.2920e+4 | 0.3447 | 64.5723 | 146.7345 | 136.5931 | 109.0339 |

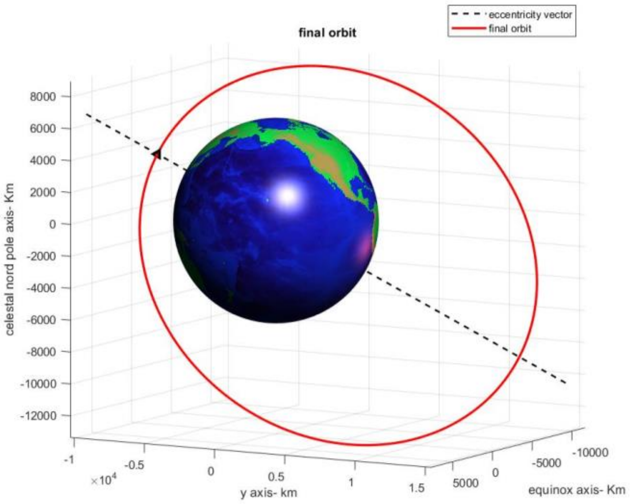
| | **X** | **Y** | **Z** | **Magnitude** |
|---|---|---|---|---|
| **r [km]** | 5.9593e+3 | 1.7114e+3 | -1.1229e+4 | 1.2827e+4 |
| **v [km/s]** | -2.4216 | 4.1582 | -2.8539 | 5.5946 |

### 3.2. Considerations and other important datas

| **E [km²/s²]** Orbital specific energy | **Shape** of orbit | **T [h]** Revolution time | **p [km]** Semi-latus rectum | **Type** of orbit |
|---|---|---|---|---|
| -15.4257 | Elliptical | 4.0598 | 1.1385e+4 | direct |

| **$r_a$ [km]** apocenter radius | **$r_p$ [km]** pericenter radius | **$v_a$ [km/s]** apocenter velocity | **$v_p$ [km/s]** pericenter velocity |
|---|---|---|---|
| 1.7374e+4 | 8.4665e+3 | 3.8774 | 7.9566 |

### 3.3 Graphical representation of the final orbit




## 4.Transfer trajectory definition and analysis

### 4.1.

Considering the data presented in tables 2.1 and 3.1, it's clear that the two orbits differ for their geometrical parameters and their orbital planes. The procedures that are going to be explained assume that, to reach the final point, it is necessary to execute manoeuvres able to achieve the final form, dimension, orbital plane and orientation in the plane.
We underline that our aim is to find the best transfer method in terms of time and variation of velocity.

### 4.2 Transfer Strategies

#### *4.2.1 Standard strategy*

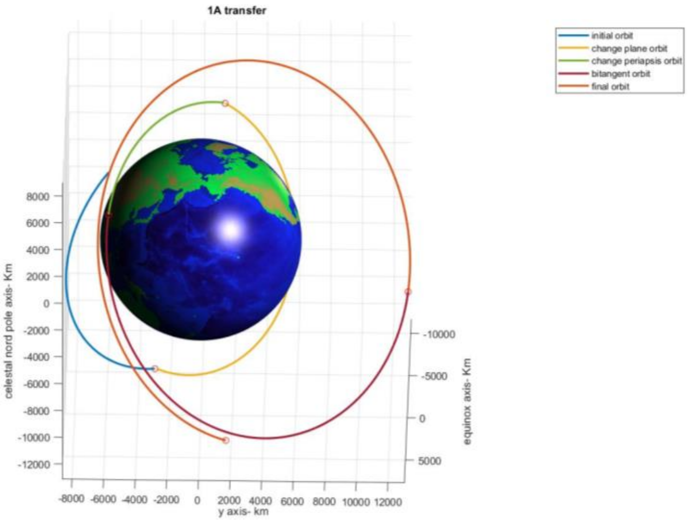
The first strategy involves, in the following order, a change of plane, a change of periapsis argument and a change of dimensions and form by a bitangent manoeuvre (pericenter – apocenter), to reach the final point.

From the initial point, the satellite arrives in the final plane described by the values of final inclination and RAAN thanks to a single impulse manoeuvre of change of plane in one of the two possible points. Afterward the satellite adjusts its own orbit by a single impulse manoeuvre of change of periapsis argument in one of the two existent point, then reaches the pericenter of the current orbit and by a bitangent transfer it makes it to the apocenter of the final orbit, concluding its journey to the target point.
The four cases presented below are different for manoeuvres point in which change of plane and change of periapsis argument take place.

| | **Strategy 1A** | **Strategy 1B** | **Strategy 1C** | **Strategy 1D** |
|---|---|---|---|---|
| Point of manoeuvre for the change of plane | θ,B= 261.1887° | θ,A= 81.1887° | θ,A= 81.1887° | θ,B= 261.1887° |
| Point of manoeuvre (*) for the change of periapsis argument | α,B=92.7332° | α,A=272.7332° | α,B=92.7332° | α,A=272.7332° |

*The point is referred to the orbit before the change of periapsis' impulse

1B(appendix, table4) strategy has the highest transfer time and total velocity variation due to a major proximity of $\theta_A$ to the focus which implies a greater ΔV, while the large amount of time is caused by the change of periapsis argument in $\alpha_A$, forcing the satellite to travel a major part of the orbit before reaching the pericenter. To avoid that, the change of periapsis argument would have been done in $\alpha_B$, as it happens in 1C strategy (appendix, table 5). However, ΔV doesn't vary due to the same magnitude of ΔV in $\alpha_A$ and $\alpha_B$. If we execute the change of plane manoeuvre in $\theta_B$ and the change of periapsis manoeuvre in the closest point $\alpha_A$, we can reduce ΔV, which is what actually happens in 1D strategy (appendix, table 6), but Δt increases due to the orientation of the orbit of change periapsis argument in the plane. Maintaining ΔV from 1D and Δt from 1C, we obtain 1A (appendix, table1) strategy which performs the change of plane manoeuvre in the most convenient point in terms of Δt and ΔV and a change of periapsis in the second possible point, convenient for reducing the Δt.
The 1A transfer procedure is the optimal and the chosen one as standard strategy.
The chosen standard strategy is taken as reference to all the others presented strategies.



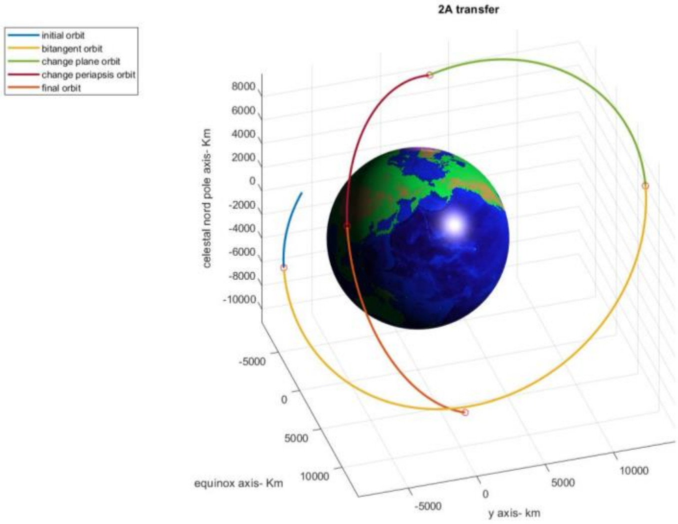

### *4.2.2 Minimum velocity strategy*

From strategy 1A (appendix, table 1) we can notice that the most demanding ΔV contribute comes from the change orbital plane manoeuvre, therefor it's convenient to reduce this term operating the change orbital plane manoeuvre between orbits with final dimensions and form, according to lecture 08, slide 5. We decided to use the Hohmann transfer strategy between apsidal points, instead of a secant one, due to the optimality of the former. The change of periapsis argument must follow the change of orbital plane manoeuvre as it is not possible to obtain the final periapsis argument and at the same time to reach the final plane with just one manoeuvre. This strategy consists in a bitangent manoeuvre, a change of plane and a change of periapsis argument. From the initial point the satellite reaches the designed apsidal point for the bitangent transfer to the designed apsidal point of an orbit with the final dimension and form, after that the satellite moves to the more convenient point of change of plane in terms of ΔV, which is always the point closest to the apocenter of the current orbit. Since the magnitude of ΔV of the change of periapsis argument is the same for the two possible points of manoeuvre, the said manoeuvre occurs in the first point met. Being in the final orbit, the satellite can travel until the assigned point. This strategy can be divided into 4 cases depending on the apsidal points where the bitangent manoeuvre takes place. It's important to underline that the true anomaly point of change of plane for these strategies is the same, as between the two possible point of manoeuvre, it's always chosen the more convenient one in terms of ΔV.

| | **Strategy 2A** | **Strategy 2B** | **Strategy 2C** | **Strategy 2D** |
|---|---|---|---|---|
| Periapsis argument of the change of plane orbit | w=213.3829 ° | w=33.3829° | w=33.3829° | w=213.3829 ° |
| Point of manoeuvre (*) for the change of periapsis argument | θ,A=2.7332° | θ,B=272.7332° | θ,B=272.7332° | θ,A=2.7332° |

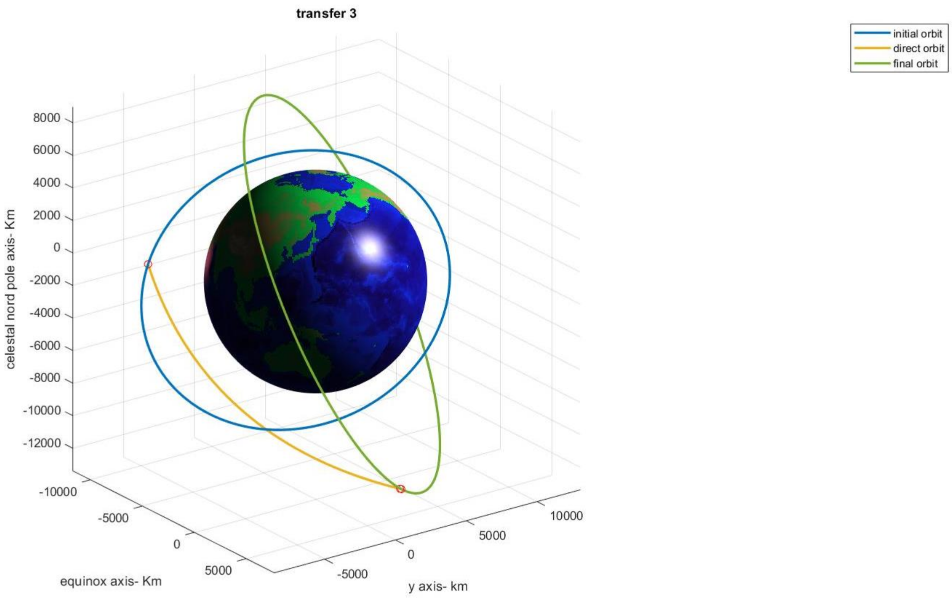
*The point is referred to the orbit before the change of periapsis' impulse

Strategy 2B (appendix,table 7) has the highest ΔV caused by the elevated contribute of change periapsis argument ΔV as $\theta_B$ is near to the point that has the greater radial velocity component (according to lecture 7, slide 10). Strategy 2C (appendix table 8) is very similar to 2B except for the bitangent transfer points of manoeuvre. Analyzing the data, it emerges that strategy 2D (appendix table 9) sensibly reduces ΔV of periapsis argument as it happens in $\theta_A$, closer to an apsidal point. On the other hand, Δt is higher than the previous strategies due to numerous revolutions around the Earth. Strategy 2A (appendix, table 2), provides a lower Δt than 2D since the satellite travels less to reach the point of change of plane, but most importantly it has lower ΔV than 2D ,thanks to the bitangent transfer between two apocenters. With this in mind, strategy 2A turns out to be the most consistent transfer strategy to minimize fuel consumption.




#### *4.2.3 Direct transfer (Appendix, table 11)*

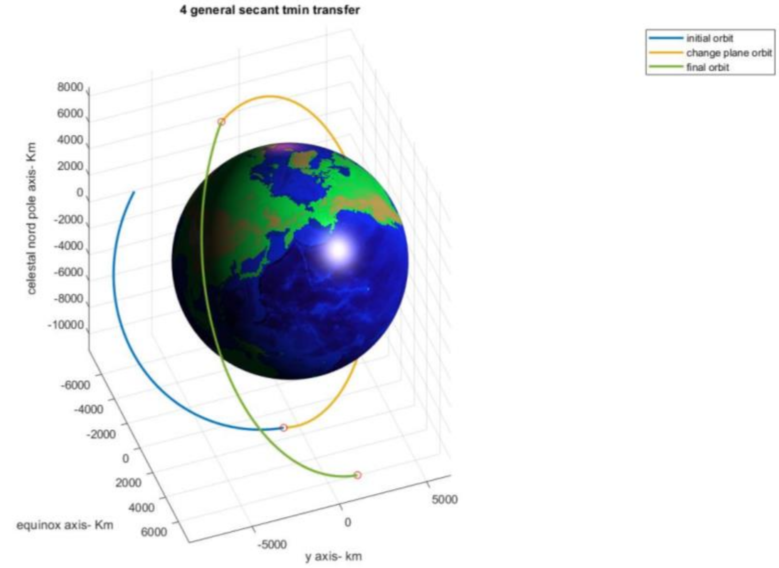
In this paragraph we analyze a direct transfer strategy made of two impulses that allows the satellite to reach the final point directly from the initial point, with the purpose of minimizing the total time of transfer. The impulses take place in the initial and final points, corresponding to two particular change of plane manoeuvres, that modifies also the geometrical parameters of the orbit. So, our purpose is to find a confocal orbit which intercepts both initial and final points. The transfer orbit belongs to a plane identified by a perpendicular versor and a point, the focus. This versor comes from the normalized vectorial product between the initial and final position vectors. Then orbital inclination and RAAN are found following their definitions (lecture 04; instead of angular momentum vector, the versor described before was used). Since the confocal transfer orbits obtainable are infinite, we choose to fix the periapsis argument in order to establish the remaining parameters, that are semimajor axis, eccentricity and true anomalies of the initial and final point. The eccentricity versor in ECI is determined by a rotation of eccentricity versor in PF, once this operation has been made, it is possible to find true anomalies, eccentricity magnitude and semi-major axis. Thanks to a MATLAB code (procedura_3), it was possible to define the periapsis argument that minimize the transfer time, eliminating the non-elliptical orbits and the inexistent ones. As expected, Δt is minimized as much as possible in response to a rise of ΔV, even higher than ΔV of strategy 1A. ΔV is found through a vectorial difference between velocity vectors, deriving the magnitude.

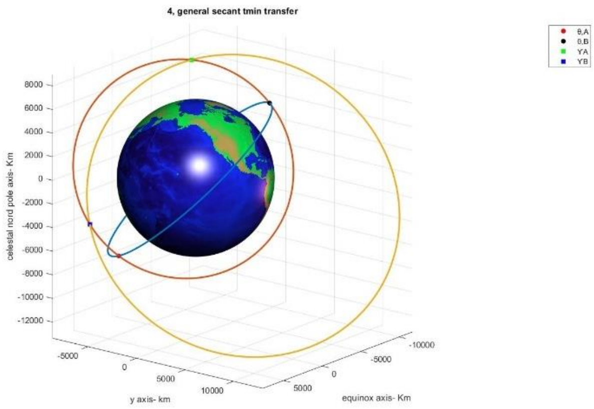



Reminding that our main aim is to decrease the amount of fuel required, it is appropriate to look for an alternative way to reduce the total transfer time, without having a variation of velocity higher than the one required in strategy 1A.

### *4.2.4 Minimum transfer time strategy (Appendix, table 10)*

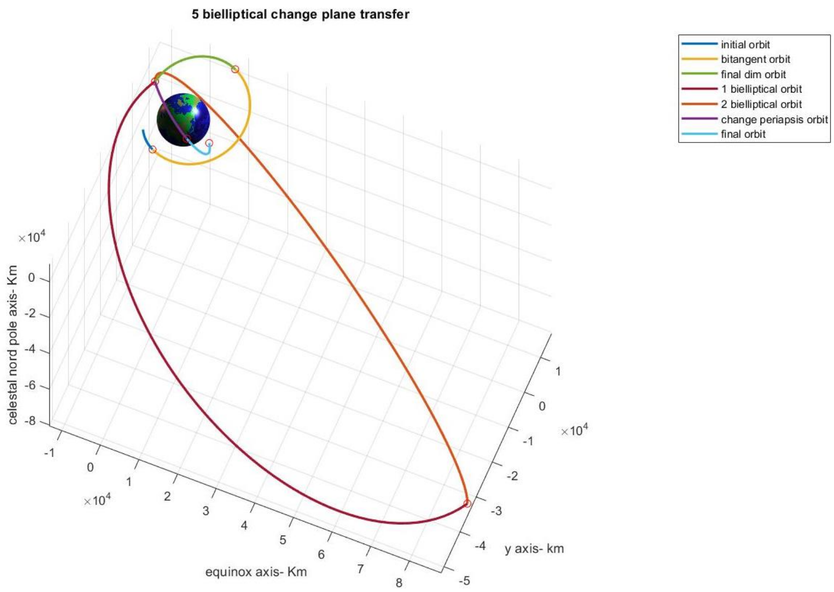
Observing the final orbit and the one of change of plane in strategy 1A, it has been noticed that they intersect in two points. Therefore, it is possible to move from the change of plane orbit to the final one through a single impulse secant manoeuvre, which allows us to introduce a strategy that reduces the total transfer time, without increasing the total variation of velocity required to perform the transfer compared to strategy 1A. From the initial point, the satellite gets to the change of plane point,$\theta_A$, then travels on the change of plane orbit until $Y_A$, the first point of intersection with the final orbit. Next, it continues its journey to the final point. The choice of $\theta_A$, instead of $\theta_B$, was led by the fact that ΔV for the change of plane is lower. The decision was not made in terms of time because Δt required to reach $\theta_B$ from $\theta_A$ in the initial orbit is the same needed in the change of plane orbit to move between the same two points. This equivalence comes from the fact that the two orbits have same dimensions and form (lecture 06,slide4). While the pick of $Y_A$, instead of $Y_B$, is bond to the purpose of reducing transfer time, as the part that the satellite has to ride in the final orbit is closer to the pericenter despite the great dimension of the orbit. Establishing the relationship between the true anomaly of the same point of manoeuvre, expressed in reference to the change of plane orbit and the final one, and the phase shift of the periapsis argument of these two orbits, we managed to calculate $Y_A$ e $Y_B$ towards the resolution of a linear trigonometric equation with parametric formulas method (matlab code manovra_secante_generale). This strategy permits to reduce significantly the total transfer time and, despite the secant manoeuvre, it also has a lower total ΔV than strategy 1A.

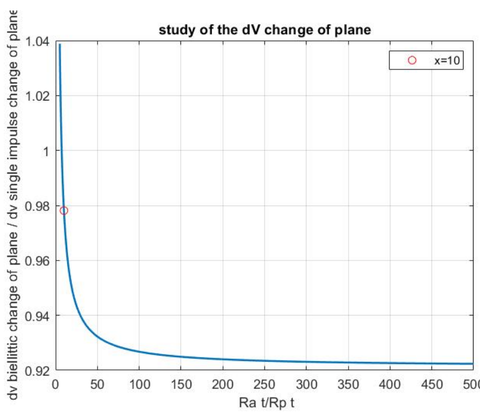



### 4.2.5. Alternative strategy (appendix table 11)

The idea behind this strategy is based on the evidence that strategy 2A has a relevant contribute of change of plane ΔV, therefor we searched an alternative way to perform the change of plane manoeuvre. The choice fell on a biellittic change of plane manoeuvre, in order to execute the pure change of plane in the more distant and suitable point from the Earth. This manoeuvre is made of:
a secant manoeuvre in $\Upsilon_A$ between the orbit with final dimension and form and a first transfer orbit built so that this manoeuvre takes place in its pericenter, a change of plane manoeuvre in the first transfer orbit apocenter which leads the satellite to a second transfer orbit with the same form and dimension of the first transfer orbit, and another secant manoeuvre in again in $\Upsilon_A$, arriving to an orbit that has the same orbital parameters of the final orbit except for the periapsis argument value. The two transfer manoeuvres have a greater dimension and eccentricity magnitude than the final orbit. The semi-major axis has been chosen in order to minimize ΔV, without taking exaggerated values (lecture 07,slide 11).
Therefor compared to strategy 2A it has been changed only the way of realizing the change of plane manoeuvre.
However, this strategy is not appropriate to achieve our goals because of its extreme total transfer time and the marginal reduction of ΔV compared to 2A.




## 5.CONCLUSION

Strategy 1A has the highest Δt between strategies 1A,2A, 3 and 4, while strategy 3 has the highest ΔV between all strategies, for this reason strategies 1A and 3 are dismissed.

Strategy 3 might be useful for missions that require a particularly quick transfer to the final point, though disregarding the amount of fuel required for the displacement.
Due to the close correlation between ΔV and mass of fuel required, we suggest realizing the mission by following strategy 2A as, even though it has a higher transfer time than strategy 4, it has the minimum ΔV. This provides a saving from an economical, structural and projectual point of view.

## 6. Appendix

Table 1: Transfer 1A

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 3.2770e+03 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 261.1887 | 8.2601 |
| | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 261.1887 | |
| 7.0524e+03 | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 92.7332 | 1.8479 |
| | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 146.7345 | 267.2668 | |
| 8.8685e+03 | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 146.7345 | 0 | 0.7824 |
| | 1.2567e+04 | 0.3825 | 64.5723 | 136.5931 | 146.7345 | 0 | |
| 1.5879e+04 | 1.2567e+04 | 0.3825 | 64.5723 | 136.5931 | 146.7345 | 180 | 0.1134 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 180 | |
| 2.5990e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 2: Transfer 2A

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 9.8827e+02 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 180 | 1.2053 |
| | 1.3806e+04 | 0.2584 | 42.0938 | 36.4000 | 213.3829 | 0 | |
| 9.0602e+03 | 1.3806e+04 | 0.2584 | 42.0938 | 36.4000 | 213.3829 | 180 | 0.2474 |
| | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 213.3829 | 180 | |
| 1.3973e+04 | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 213.3829 | 261.1887 | 7.0383 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 141.2681 | 261.1887 | |
| 1.6419e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 141.2681 | 2.7332 | 0.1945 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 357.2668 | |
| 1.9273e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 3: Transfer 4

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 3.2770e+03 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 261.1887 | 8.2601 |
| | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 261.1887 | |
| 7.9261e+03 | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 127.3170 | 2.6005 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 301.8505 | |
| 1.1911e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 4: Transfer 1B

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 6.7914e+03 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 81.1887 | 8.6160 |
| | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 81.1887 | |
| 1.2042e+04 | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 272.7332 | 1.8479 |
| | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 146.7345 | 87.2668 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1.8848e+04 | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 146.7345 | 0 | 0.7824 |
| | 1.2567e+04 | 0.3825 | 64.5723 | 136.5931 | 146.7345 | 0 | |
| 2.5858e+04 | 1.2567e+04 | 0.3825 | 64.5723 | 136.5931 | 146.7345 | 180 | 0.1134 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 180 | |
| 3.5969e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 5: Transfer 1C

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 6.7914e+03 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 81.1887 | 8.6160 |
| | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 81.1887 | |
| 7.0524e+03 | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 92.7332 | 1.8479 |
| | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 146.7345 | 267.2668 | |
| 8.8685e+03 | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 146.7345 | 0 | 0.7824 |
| | 1.2567e+04 | 0.3825 | 64.5723 | 136.5931 | 146.7345 | 0 | |
| 1.5879e+04 | 1.2567e+04 | 0.3825 | 64.5723 | 136.5931 | 146.7345 | 180 | 0.1134 |
| | 1.2920e+0.4 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 180 | |
| 2.5990e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 6: Transfer 1D

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 3.2770e+03 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 261.1887 | 8.2601 |
| | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 261.1887 | |
| 3.5457e+03 | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 321.2681 | 272.7332 | 1.8479 |
| | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 146.7345 | 87.2668 | |
| 1.0351e+04 | 8.9993e+03 | 0.1377 | 64.5723 | 136.5931 | 146.7345 | 0 | 0.7824 |
| | 1.2567e+04 | 0.3825 | 64.5723 | 136.5931 | 146.7345 | 0 | |
| 1.7361e+04 | 1.2567e+04 | 0.3825 | 64.5723 | 136.5931 | 146.7345 | 180 | 0.1134 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 180 | |
| 2.7473e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 7: Transfer 2B

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 9.8827e+02 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 180 | 0.1425 |
| | 9.3523e+03 | 0.0947 | 42.0938 | 36.4000 | 33.3829 | 180 | |
| 5.4888e+03 | 9.3523e+03 | 0.0947 | 42.0938 | 36.4000 | 33.3829 | 0 | 0.7776 |
| | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 33.3829 | 0 | |
| 1.7709e+04 | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 33.3829 | 261.1887 | 7.0383 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 321.2681 | 261.1887 | |
| 1.8112e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 321.2681 | 272.7332 | 4.0746 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 87.2668 | |
| 1.8923e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 8: Transfer 2C

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 5.2364e+03 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 0 | 0.7824 |
| | 1.2567e+04 | 0.3825 | 42.0938 | 36.4000 | 33.3829 | 0 | |
| 1.2247e+04 | 1.2567e+04 | 0.3825 | 42.0938 | 36.4000 | 33.3829 | 180 | 0.1134 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 33.3829 | 180 | |
| 1.7159e+04 | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 33.3829 | 261.1887 | 7.0383 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 321.2681 | 261.1887 | |
| 1.7562e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 321.2681 | 272.7332 | 4.0746 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 87.2668 | |
| 1.8373e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 9: Transfer 2D

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 5.2364e+03 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 0 | 0.3232 |
| | 8.1135e+03 | 0.0435 | 42.0938 | 36.4000 | 33.3829 | 0 | |
| 8.8730e+03 | 8.1135e+03 | 0.0435 | 42.0938 | 36.4000 | 33.3829 | 180 | 1.2461 |
| | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 213.3829 | 0 | |
| 2.1093e+04 | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 213.3829 | 261.1887 | 7.0383 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 141.2681 | 261.1887 | |
| 2.3539e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 141.2681 | 2.7332 | 0.1945 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 357.2668 | |
| 2.6393e+04 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 10: Transfer 5

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 9.8827e+02 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 180 | 1.2053 |
| | 1.3806e+04 | 0.2584 | 42.0938 | 36.4000 | 213.3829 | 0 | |
| 9.0602e+03 | 1.3806e+04 | 0.2584 | 42.0938 | 36.4000 | 213.3829 | 180 | 0.2474 |
| | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 213.3829 | 180 | |
| 1.3973e+04 | 1.2920e+04 | 0.3447 | 42.0938 | 36.4000 | 213.3829 | 261.1887 | 2.9546 |
| | 6.6107e+04 | 0.8182 | 42.0938 | 36.4000 | 114.5715 | 0 | |
| 9.8550e+04 | 6.6107e+04 | 0.8182 | 42.0938 | 36.4000 | 114.5715 | 180 | 0.9751 |
| | 6.6107e+04 | 0.8182 | 64.5723 | 136.5931 | 42.4567 | 180 | |
| | 6.6107e+04 | 0.8182 | 64.5723 | 136.5931 | 42.4567 | 0 | 2.9546 |
| 1.8313e+05 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 141.2681 | 261.1887 | |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 141.2681 | 2.7332 | 0.1945 |
| 1.8557e+05 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 357.2668 | |
| 1.8843e+05 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |

Table 11: Transfer 3

| t (s) | a (km) | e (-) | i (deg) | Ω (deg) | ω (deg) | θ (deg) | Δv (km/s) |
|---|---|---|---|---|---|---|---|
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | |
| 0 | 8.9993e+03 | 0.1377 | 42.0938 | 36.4000 | 33.3829 | 147.4147 | 6.0822 |
| | 9.1939e+04 | 0.9062 | 78.8745 | 36.8867 | 225.00 | 315.5449 | |
| 2.3250e+03 | 9.1939e+04 | 0.9062 | 78.8745 | 36.8867 | 225.00 | 71.8518 | 8.7853 |
| | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |
| 2.3250e+03 | 1.2920e+04 | 0.3447 | 64.5723 | 136.5931 | 146.7345 | 109.0339 | |