Human Spaceflight SD2905

Operations and Logistics Red Team

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0. Introduction

As our group dealt with Operations and Logistics for a travel to Mars, we needed to aim the topics Routes and Duration, operations around planets, resupply and partly also the topic of communication.

In our first group meeting we posed some questions that we should answer during our project. Regarding the routes and duration we thought of which route to take basing on the length of the transfer, and the timeslots that can be used. Regarding the operations aound the planets, we wanted to figure how we are resupplying and refuelling the space ship, how we are transfering the humans, both from Earth and from Mars and how much supplies are needed. Finally, for the communications, we hypotized the presence of a communication-base on Mars. We also want to calculate the timeshift between the space ship and Earth that could shrink communication possibilities.

In the end of our report we are going to give an off nominal case related to our topic.

1. Routes and Duration

1.1. Methodology

The first challenge our team decided to face, was selecting the route to go to Mars. The decision we took in the first group meeting was neither to use simply some tabled data nor the data obtained by simplified computations that make the assumption of coplanar circular orbits. The first step was then to access the real data for the planets' positions and orbits. The source we used was JPL's HORIZONS.

Throughout all the iterations we utilized a simple scheme, that was to initialize our research of the optimum by producing a grid of initial conditions for the transfer. Then we would proceed to creating an optimization problem to minimize the delta-v budget utilizing the starting point found in the preliminary grid estimate. For the computations we relied on self written Matlab functions and optimization algorithms. The approach we used is called "Patched-Conics" and is typical of phase-alpha projects. It consists in considering the sphere of influence of the planets as infinitesimal until you reach them, and infinite once you are inside of them. Moreover the time inside the sphere of influence of the planets is neglected while performing a fly-by maneuver.

The initial condition around Earth was considered to be a circular orbit in LEO (400 Km altitude) so that it would be regular in time, and would not be too much of a strain for the launcher to meet the velocity of the station in space while docking for resupplies. Moreover it would not be reached by trapped particles in the lower radiation belt and the orbit would last longer due to a smaller drag force. To reduce the launcher requirements it was also desirable for the launch site to be closer to the equator, so that we would be able to exploit Earth rotation with the launcher. Moreover we had to take into account the launcher selection, and the team proposed using the ITS, so we decided to follow SpaceX actual launch site, Cape Canaveral. The arrival position around Mars was more or less equatorial and circular for the same reasons.

The initial analysis did not take into account aerobraking as the Vehicle Concept group wanted to avoid it. Therefore all of the costs are computed considering powered maneuvers, but a comparative cost is also shown in the tables.

1.2. First Iteration

Once we had the baseline for all our iterations, we proceeded with the analysis of the first strategy. The first iteration was performed considering a direct transfer from Earth to Mars and back. This allowed a rough estimation of preliminary data such as costs (in terms of delta-v budget) and time durations. The data mentioned can be observed in the following pictures.

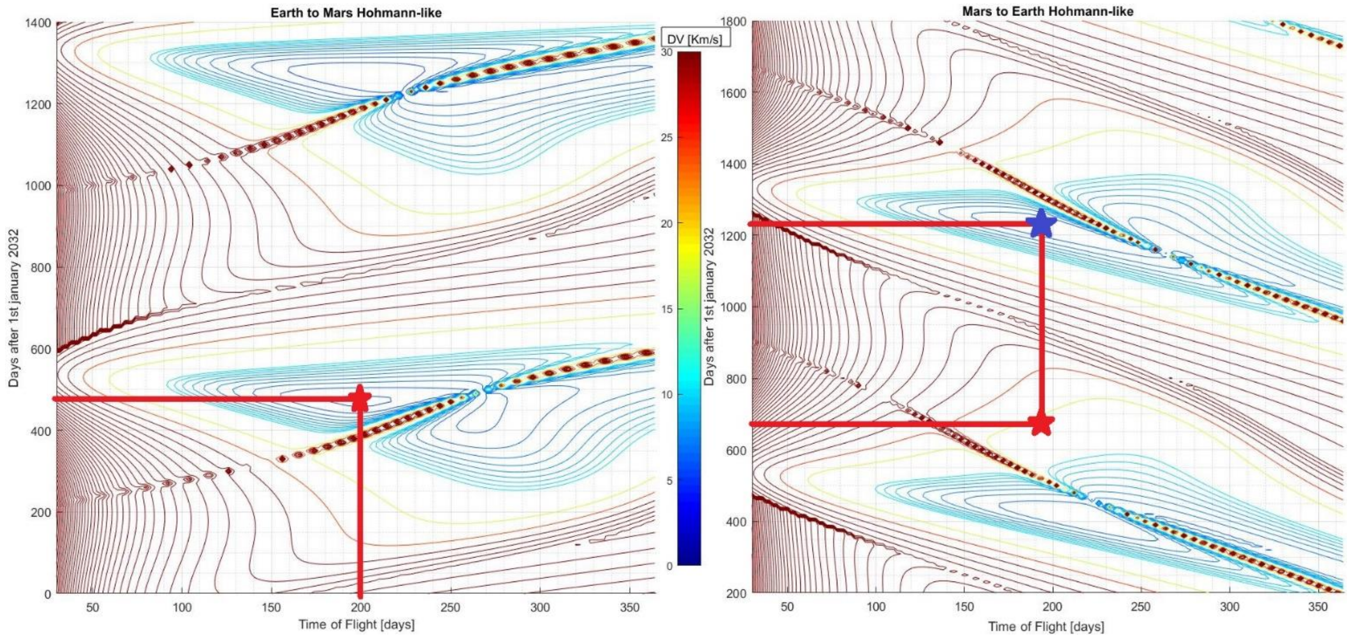

Figure 1: Porkchop plot for Hohmann-like transfer. The red star accounts for the arrival position at Mars, The blue Star accounts for the departure date from Mars.

The two graphs represent a Porkchop plot for this strategy that we will call Hohmann-like. It is clear how the launch windows will be regular in time. Also the choice of time of the stay on Mars is determined by the time at which one can have the smallest cost for the total transfer. The details for this computations are given in the results section. The mission profile when considering aerobraking possibility would include an impulsive maneuver to enter a highly elliptic orbit around Mars (or Earth), then an aerobraking phase and finally a circularization pulse given to obtain the desired radius.

A representation of the transfer is given here:

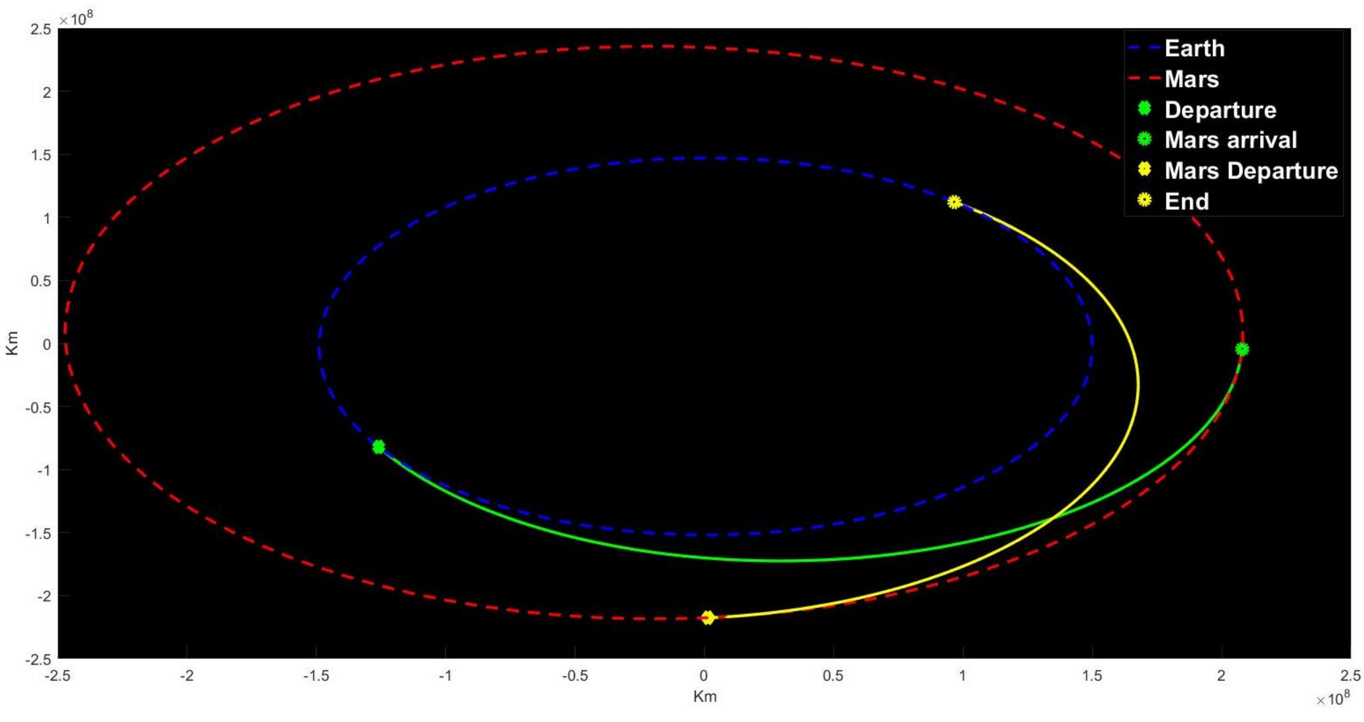

Figure 2: Hohmann-like transfer. The shape of the orbits is influenced by the visualization in 2D of 3D orbits.

1.3. Second Iteration

The second iteration, as requested from the rest of the team, was performed considering also the flyby at Venus while coming back from Mars: this would allow us a shorter stay on the planet, This means that it is possible to use the spaceship for more flights than with the Hohmann transfer, because the Hohmann transfer needs more than 800 days and, due to this reason, only every second launch window from Earth can be used. In fact this trip would last approximately 630 days between departure and arrival, which is shorter than the 800 days of the launch windows. However a problem that was evidenced by the computation, is that this flyby is not possible at all time windows.

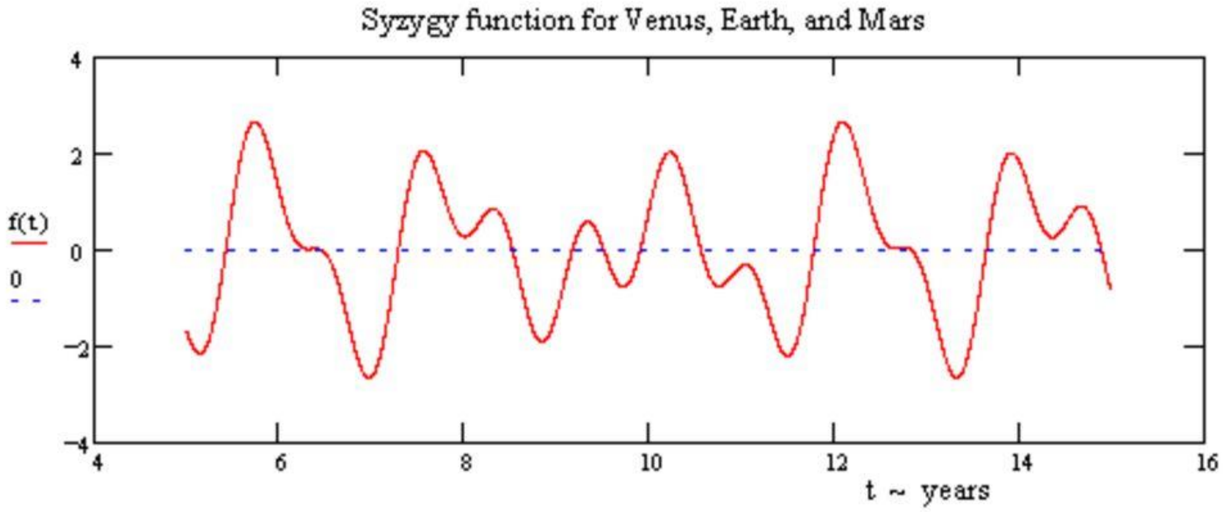

Figure 3: Synchronization function between Earth, Mars and Venus. The synchronization is equal every time the f(t) has an inflection point at 0.

As can be shown from the picture above, the graphs show an index of the synchronization between the orbits of Venus, Mars and Earth. If the position is ideal on the first launch window, it will be only ideal and exactly equal to the one reported in the tables after 6 years, or when the index of synchronization is zero again. This would not guarantee a regularity in the transfers which was in fact the objective of the whole team: to provide a “space-bus”. The Hohmann-like transfer would have been much more regular and predictable in terms of costs and time durations. The reason for this has to be found in the concept of synodic period. To compute the synodic period for two planets one need to take into account the revolution time of each of these two. In fact the synodic period is defined as the period of time that intercurs between two instants in which the aforementioned planets have the same relative position. Having said that, it is clear that only taking into account the synodic period of Earth and Mars would give a much better result with respect to having to add also the Venusians period (or any other planet’s) into the equation. The mission profile for aerobraking is modified in the same way as for the Hohmann-like transfer to obtain a fair comparison.

A representation of the transfer is given here:

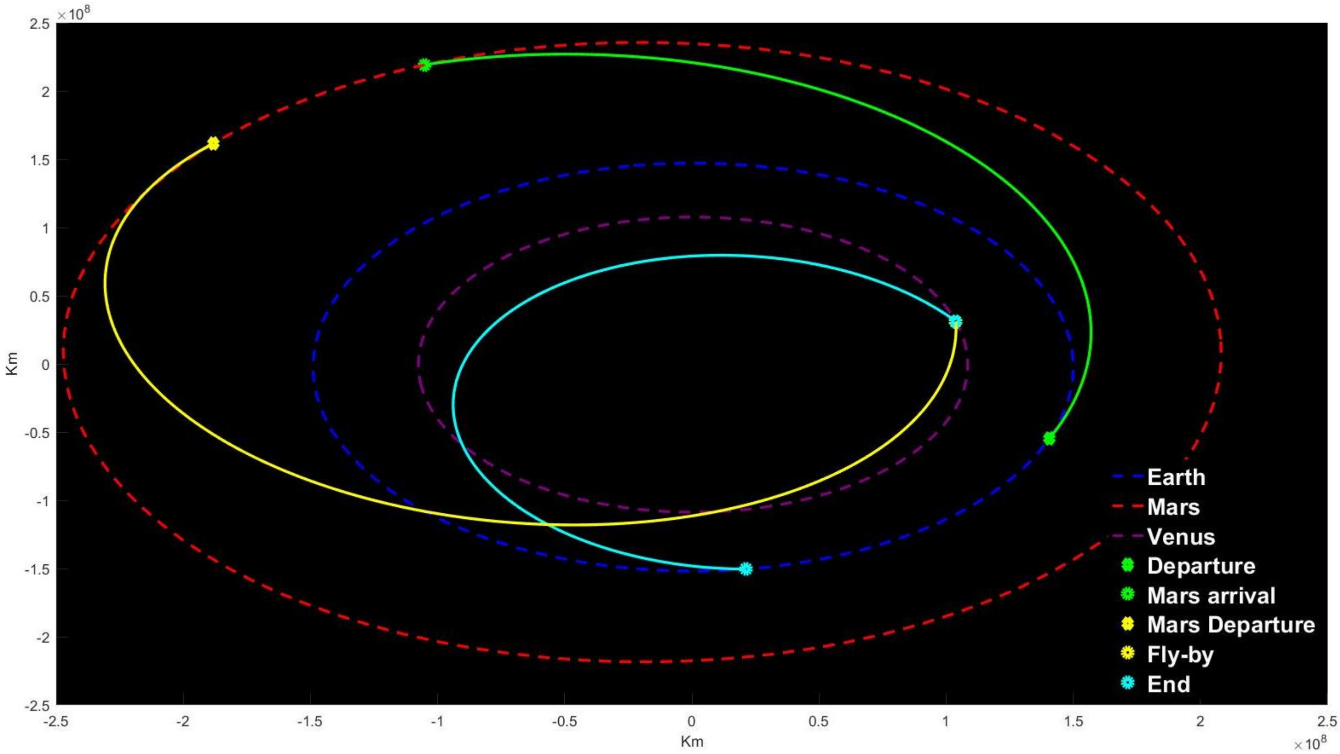

Figure 4: Interplanetary transfer with Venus Fly-by. The shape of the 3D orbits is influenced by the 2D visualization.

1.4. Third Iteration

The third and last alternative that we considered were the cycloid orbits. The most relevant one was obtained were described in the paper [1] with the names "up-escalator" and "down-escalator". The problem that we faced with the cycloid orbits was that there was not enough comparative material to rely on, since most of the studies utilized simplified orbits. Moreover we found out that in order for the strategy to works we would have needed two vehicles, one for the outgoing trajectory and one for the incoming trajectory. The travel time would be too long if using the "up-escalator"also to come back and the "down-escalator" to get to Mars (as shown in table 3). Therefore this would have increased the costs a lot, and also it would have been hardly possible to realize by 2032 because it would require an initial considerable investment without seeing any immediate result. To cap it all, the main advantage of using such orbits was to avoid having to spend fuel to go to Mars, but those orbits needed corrections nonetheless at every period. Furthermore the costs for matching their speed were too high, giving also only one opportunity for the docking every 2.14 years since they only perform a fly-by at Earth without closing the orbit. The picture representing these orbits is shown in figure 5.

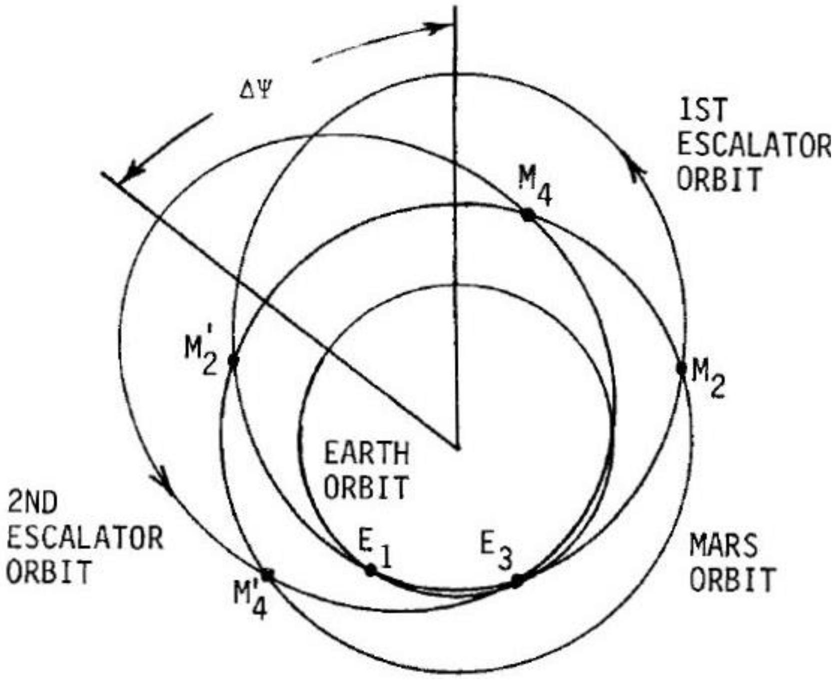

Figure 5: Escalator orbit representation.

2. Results

Maneuver	Hohmann-like Powered [Km/s]	Hohmann-like Aerobraking [Km/s]
Leave LEO	3.62	3.62
Mars' Orbit Insertion	2.40	1.14
Mars Circularization	//	0.1
Leave LMO	2.23	2.23
Earth's Orbit Insertion	3.64	aerobraking
Earth Circularization	//	0.6
TOTAL	**11.89**	**7.69**

Table 1: Delta-v budget for the Hohmann mission profile.

Maneuver	Venus fly-by Powered [Km/s]	Venus fly-by Aerobraking [Km/s]
Leave LEO	3.58	3.58
Mars' Orbit Insertion	2.40	1.18
Mars Circularization	//	0.1
Leave LMO	4.11	4.11
Earth's Orbit Insertion	3.64	aerobraking
Earth Circularization	//	0.6
TOTAL	**13.73**	**9.57**

Table 2: Delta-v budget for the Venus fly-by mission profile.

Maneuver	Earth Access Cost [Km/s]	Mars Access Cost [Km/s]	Earth-Mars time [days]	Mars-Earth time [days]
Up-Escalator	4.8	9.4	157	624
Down-Escalator	4.7	9.2	624	157

Table 3: Cycloid Orbits, third strategy considered.

The total DV budget for the Hohmann-like transfer without considering landing and take off at Mars will be approximately 11.89 Km/s. This is just a rough estimate since we did not take into account corrections of the orbit around Mars for 540 days estimated in the order of 0.4 Km/s and trajectory corrections maneuvers in space before arriving to Mars and back to Earth that will account for 0.1Km/s. If we decided to account for aerobraking both at Earth and at Mars, a total cost of 7.7Km/s for the whole interplanetary mission would be possible. All the data can be observed in detail in table 1.

When considering the Venus Fly-by trajectory the optimal solution found suggested a DV budget for the whole mission of 13.73Km/s. The biggest difference was brought by the DV necessary to leave Mars' orbit and reach Venus for the Fly-by (4.11Km/s vs. 2.23Km/s of the Hohmann strategy). When using the aerobraking maneuvers both at Earth and at Mars the total DV budget could be reduced at approximately 9Km/s. All the data can be detailed in table 2.

As far as time durations are concerned, we can show them in the following table.

	Hohmann-like [days]	**Venus-Fly-by [days]**
Earth-Mars travel time	189	190
Residence time on Mars	544	38
Mars-Earth travel time	199	372
TOTAL	**932**	**600**

Table 4: Time durations for the different mission profiles.

The main differences between the two strategies are residence time on the surface and travel time to come back from Mars. For the Hohmann-like transfer, the time on the surface is the one between the blue and red star on the right in figure 1 and it is approximately 540 days. The travel time between Earth and Mars will be 199 days and the one to come back will be 189 days as can be also observed in figure 1.

For the Venus Fly-by strategy (nominal case) the permanence time on the red planet would be of 38 days, with a travel to go to Mars of 190 days and the travel to come back of 372 days which is almost two times higher than the one for the first mission profile.

Finally we presented all our alternatives to the team that held two votings. On the first preliminary one, the cycloid orbits where chosen. However, when faced by the costs and all the forementioned problems, the final decision after the second vote indicated the Hohmann transfer to be the one of our choice.

The decision of the Hohmann transfer was also heavily influenced by the Human Aspects group that propended towards using a smaller time in space with respect to the Venus Fly-by strategy. Also the Propulsion team wanted a lower the delta-v budget and finally it was our own decision that verted to such strategy because of the predictability and simplicity of its realization.

3. Operations Around Planets

Now that the routes between planets are know, the overall mission plan can be sketched. The results of all the decisions from the different groups is shown on the next figures :

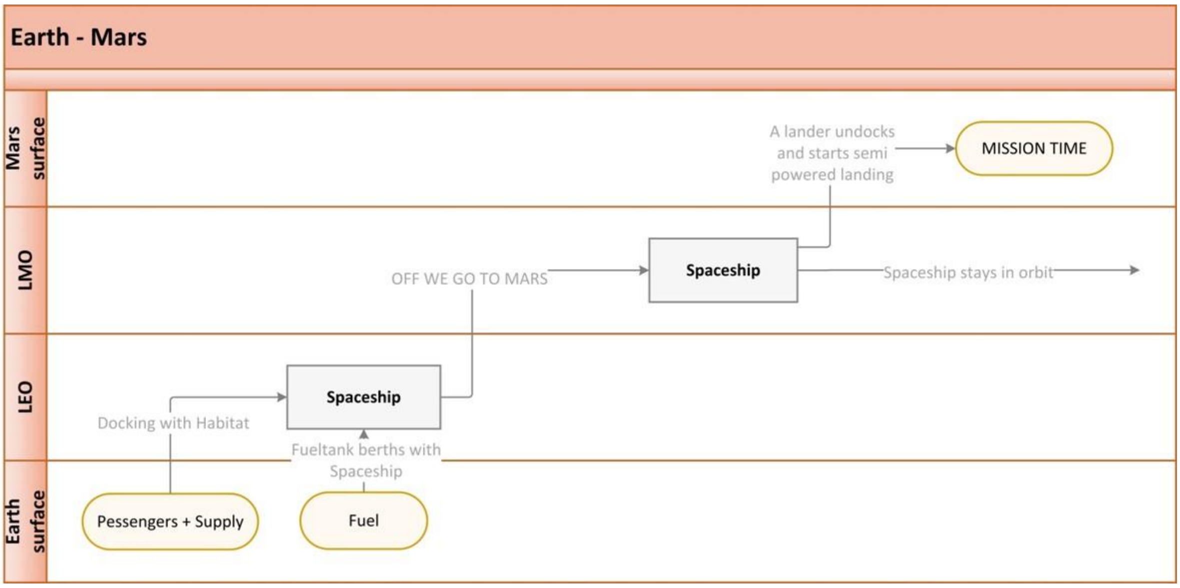

Figure 6: Mission plan from Erath to Mars

The spaceship which is transporting the passengers from Earth to Mars is assumed to be already in LEO. The first thing to do is to ressuply it, this is done by 2 ITS launchers. One will first bring the passengers and all the supplies (i.e. food, water, air system consumables, …) and then the second one will bring the fuel to the spaceship. After these operations, the spaceship is ready to go to Mars. Once in LMO, the passengers will land with the same lander sent on the first ITS launcher to bring them for Earth surface to LEO and the spaceship will remain in LMO.

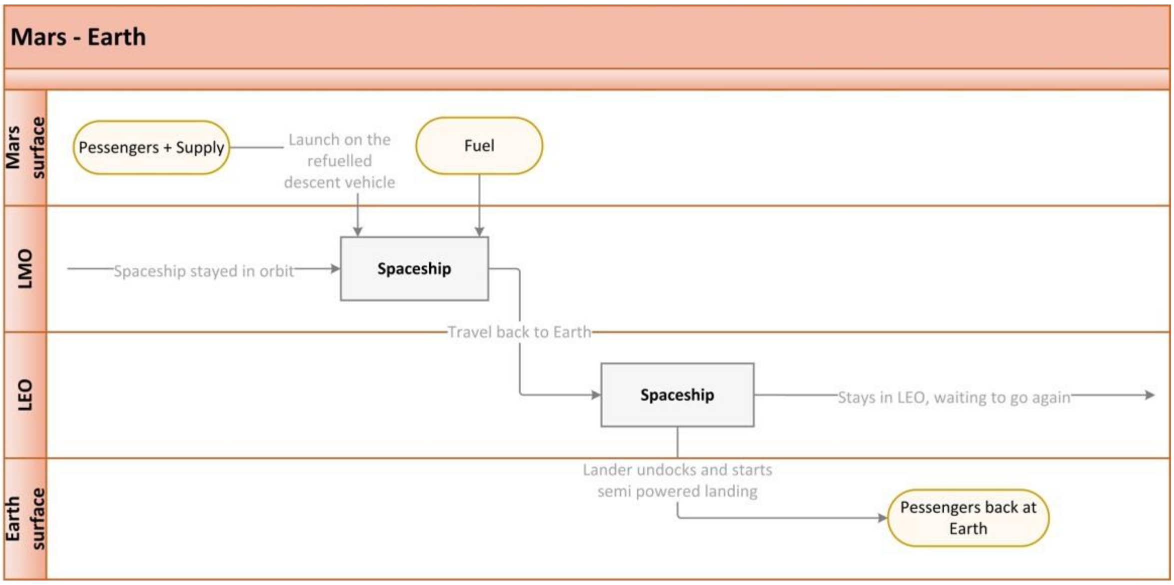

Figure 7: Mission plan from Mars to Earth

The plan to get back from Mars is basically the same as the way to get there. First, the passengers return on the spaceship from Mars surface with the lander vehicle. Then the spaceship is refuelled with an ITS that we assume has been sent to Mars before the mission. The spaceship goes back to Earth and the passengers can land thanks to the same lander.

In the following table the masses and volumes involved in the resupplies are shown :

<table>
<tr><th colspan="2">Type of resupply</th><th>Weight (tons)</th><th>Volume (m3)</th><th>Total mass per launch (tons)</th><th>Total volume per launch (m3)</th></tr>
<tr><td colspan="2">Fuel (H2)</td><td>264,1</td><td>3521</td><td>264,1</td><td>3521</td></tr>
<tr><td colspan="2">Food</td><td>8,3</td><td>15,6</td><td rowspan="7">36,8</td><td rowspan="7">114,8</td></tr>
<tr><td colspan="2">Water</td><td>6,33</td><td>6</td></tr>
<tr><td rowspan="4">Air system consumable</td><td>Oxygen</td><td>6,5</td><td>4,56</td></tr>
<tr><td>LiOH Canisters</td><td>6,3</td><td>2,7</td></tr>
<tr><td>Nitrogen</td><td>3,05</td><td>3,02</td></tr>
<tr><td>Hydrogen</td><td>0,61</td><td>6,94</td></tr>
<tr><td colspan="2">Passengers and luggages</td><td>5,7</td><td>76</td></tr>
<tr><td colspan="4">ITS Payload to LEO Capacity</td><td>300</td><td>8000</td></tr>
</table>

Table 5: Masses and volumes involved in the resupply done on Earth

These figures stand for the ressuply on Earth but they are the same for the ressuply on Mars expect for the fuel which is only 233.2 tons for a volume of 3109 m3 for the ressuply on Mars.

<table>
<tr><th colspan="2">Type of resupply</th><th>Weight (tons)</th><th>Volume (m3)</th><th>Total mass per launch (tons)</th><th>Total volume per launch (m3)</th></tr>
<tr><td colspan="2">Fuel (H2)</td><td>233,1</td><td>3109</td><td>264,1</td><td>3109</td></tr>
<tr><td colspan="2">Food</td><td>8,3</td><td>15,6</td><td rowspan="7">36,8</td><td rowspan="7">114,8</td></tr>
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<tr><td colspan="2">Passengers and luggages</td><td>5,7</td><td>76</td></tr>
<tr><td colspan="4">ITS Payload to LEO Capacity*</td><td>270</td><td>8000</td></tr>
</table>

*Table 6: Masses and volumes involved in the resupply done on Mars; *LMO capacity will be bigger due to lower gravitational pull on Mars*

Air, food and water consumables are equal as the Human Aspects team designed the two way trip in the same way (190 days both cases).

4. Communications

Once we settled for the interplanetary transfer it was time to face the rest of the problems, first of all the estimated distances and time delays between the spacecraft and the two planets are represented in the following figures.

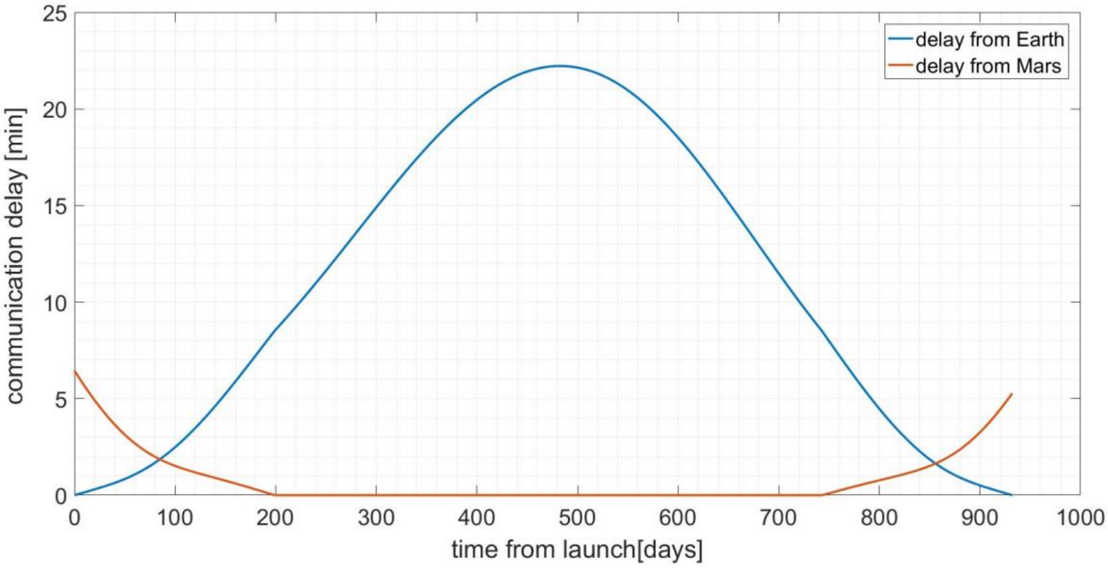

Figure 8: Delays in communications of the spacecraft from Earth and Mars in minutes.

The decision for the antenna was settled by the Vehicle Concept group, they selected an high gain antenna of 1KW of power. The maximum delay with respect to planet Earth is 23 minutes, but this only happens once we are already in orbit around Mars and we can assume that a more powerful station will be available on Mars surface. Therefore the maximum distance that we have to compensate for on our spacecraft is for a delay in communication with respect to Earth of 7.5-8 minutes as can be seen from figure 8.

5. Future Missions

Since this mission is meant to be repeated, it is needed to think about the future missions and how often we can travel between the two planets. The launches windows are shown on the following graph:

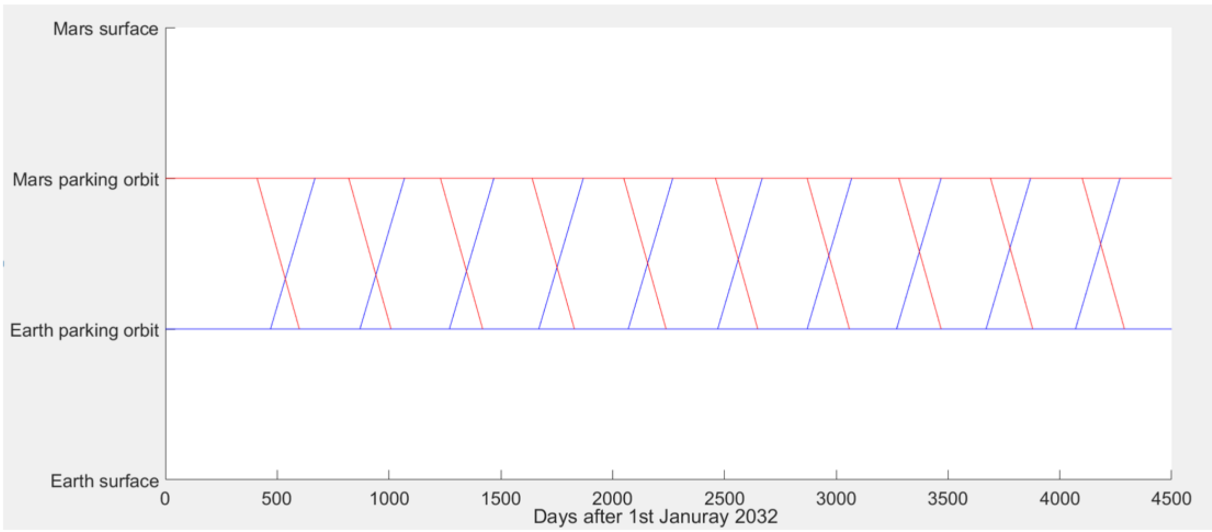

Figure 9: Future travels beatween Earth and Mars

As it can be seen, a departure is possible every 800 days approximately, since our mission lasts 930 days. This means that there is an overlapping in missions and, as a single spaceship is available, humans can only travel every 4.4 years to Mars, which is the plan for the moment. The crew should leave Earth two days before the optimal launch date to Mars, this ensures to have enough time to perform the two dockings necessary to resupply the ship (~24h each).

6. Off Nominal Case

After the discussion with the team, we realized that such a mission cannot have any fault in the mission profile as far as the orbital maneuvers are concerned. This however is never a good choice, it is in fact necessary in order to achieve the human rating to take into account the possibility of the thruster malfunction. Having a “safe” option to come back is also what drove Houbolt and his team in the choice of a free return trajectory from the Moon during the Apollo programme. When they developed a mission profile, they took into account that the trajectory should allow the spacecraft to return into Earth’s sphere of influence without any need of propulsion should the main engine fail.

Due to this fact we decided that it was a wise choice to try to render the trajectory safer. Therefore we chose the following to be our off nominal condition.

What happens if a meteoroid causes a loss of propellant, or if a trajectory correction maneuver too many is necessary.

The countermeasures for this are fairly simple, but they exploit the most important features of our work.

- The first step would be to perform at least one EVA with two trained members of the crew to try and stop the flow of hydrogen from the tank. In order to do this, the members of the crew have a large amount of tools, moreover hydrogen is not an explosive when not combined with an oxidizer as in our case.
- The second step is to assess how much fuel is left in the ship. Should the necessary amount to stop the ship around Mars in the desired orbit be missing, one can exploit the attitude control engines.
- The third step while approaching Mars is to aim for a perigeum of 120Km. At this altitude above the surface, most of the past missions to Mars as for example the Mars Global Surveyor performed safely an aerobraking maneuver. The reason is that the atmosphere of Mars is really thin, and at 120Km it is enough drag to slow down the spacecraft without putting too much stress on the structure.
- The fourth step is to brake as much as possible and send the ship in an highly elliptical orbit (preferably one with eccentricity 0.9).
- The fifth step is simply waiting for the aerodynamic drag to perform its job. The overall effect is to lower the eccentricity of the orbit and the semimajor axis, rendering the orbit more circular. As the apogeum altitude drops, one last maneuver is necessary.
- The sixth step is to finally detach from the main ship and safely land all the passengers with a complete aerobrake maneuver, that will slow down the spacecraft plus possibly all the remaining propellant.
- The last step is a circularization maneuver that will impact with a total 0.1 Km/s, also this maneuver can be performed with attitude engines automatically. The maneuver must be performed at perigeum of the orbit so that the final shape will be the circular desired one at 400Km altitude.

If the described steps are followed the main ship will be safe around Mars orbit and there will be no casualties. Also the main ship will stay in orbit until further maintenance can be performed to check if any damage originated from the use of aerobraking, but in order to do this without missing the next launch window, the crew and people on Mars have 540 days.

The computation for our off nominal design condition were performed considering al the perturbations that the orbit has around Mars. The equations describing this process are computed exploiting Lagrange's planetary equations as described in [2]. The perturbations included are:

- Aerodynamic drag: with a simplified exponential model of the atmosphere;
- J2: non uniform mass distribution of Mars;
- Third body presence: the most influential being the Sun;
- Solar Pressure making for simplicity the assumption that the surface exposed to aerodynamic drag is the same amplitude as the one exposed to solar pressure;

Their effect is shown in figure below, averaged on each period so as to avoid too many points in the graphs.

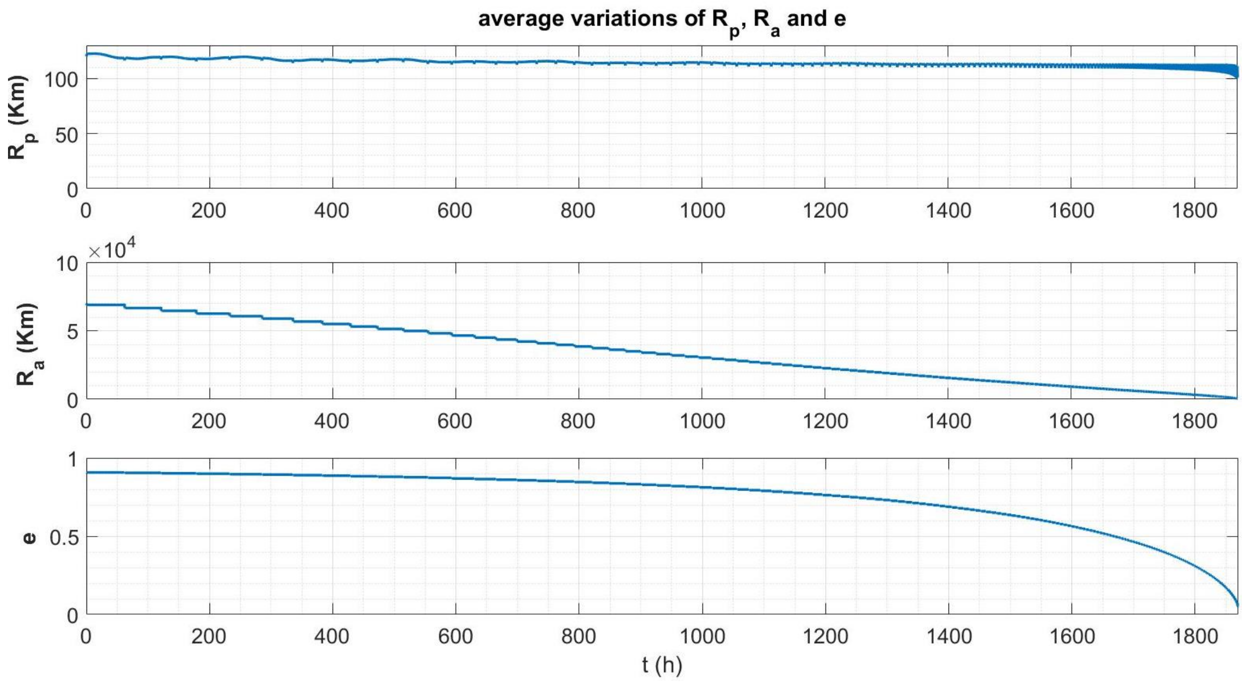

Figure 10: Aerobraking effect on orbit, in case of emergency braking.

As can be seen from figure 10, the eccentricity will decrease, as the apoapsis altitude, instead the periapsis altitude will be almost the same except in the end when more time is spent closer to the atmosphere and also some numerical error may occur. The overall result show a feasibility of the aerobraking maneuver for the main ship with a total time of 75 days to bring it to the final orbit.

7. Conclusion

During this project we designed an entire journey back and forth from Earth to Mars.

We first had to figure out how to go on Mars, thing that has never be done and is just theortical for the moment. We tried different routes between the two planets and choose one to sketch the entire mission. Next step was to design the ressuply phase and the landings on Earth and Mars. The communications between the spaceship and the planets was also covered as well as an off-nominal case.

Last step was to plan the future of this mission and to try to know when future missions can be performed.

8. Bibliography

[1] Circulating transportation orbits between earth and Mars Article · February 1986 DOI: 10.2514/6.1986-2009 · Source: NTRS;

[2] Battin, Richard H., An introduction to the mathematics and methods of astrodynamics. Page 484 chapter 10, sec 10.2. American Institute of Aeronautics and Astronautics, Inc.; 1801 Alexander Bell Drive, Reston, VA 20191. ISBN 1-56347-342-9