Mounting Olympus Mons - Mars Operations

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***Abstract*—This report assesses the requirements and proposed solutions for Mars operations for the Mars mission Hephaestus during which at least one astronaut must mount Olympus Mons. The report starts by discussing on-site means of transportation. The descent vehicle that landed the astronauts will be used again to take them from the landing site at 10 km below the top of Olympus Mons back to the base. Two rovers are then used to complete the mission and accompany the selected part of the crew to the summit. The best option for the rovers is assessed to be NASA's manned pressurised rover concept *Space Exploration Vehicle (SEV)*. After considering batteries and solar cells for power supply, Methane direct fuel cells are selected. The different trajectories and Δv needed for the Hopper are studied to eventually choose an elliptic trajectory. Means of communication are also discussed. To ensure reliable communication on the Martian surface, a satellite constellation solution based on a previous study is suggested. The overall timeline on Mars is presented, built from the results and requirements. Lastly, off-nominal scenarios are eventually considered for Mars operations.**

***Index Terms*—Human Spaceflight, Mars, Olympus Mons**

***Sammanfattning*—Den här rapporten utvärderar de krav och föreslagna lösningar för de verksamheter som kommer ske på Mars under uppdraget Hephaestus, där minst en astronaut ska bestiga Olympus Mons. Rapporten börjar med att diskutera de färdmedel som kommer användas. Raketen som landat med astronauterna ska användas igen för att ta dem från landningsplatsen till 10 km nedan toppen av Olympus Mons. Två rovrar kommer användas för att ta astronauterna från den punkten till en kilometer nedan toppen och kommer sedan färdas bakom astronauterna när de tar sig till toppen. Det bästa alternativet som rover är NASA:s koncept till en bemannad, trycksatt rover som kallas "Space Exploration Vehicle" eller SEV. Efter att ha övervägt batterier och solceller bestämdes det att metandrivna bränsleceller ska använda i dessa rovrar. De olika banorna och hastighetsökning för raketen studerades och en elliptisk bana valdes. Hur kommunikationen ska se ut på Mars diskuteras också. För att garantera att det finns kontinuerlig kommunikation på Mars yta föreslås en satellitkonstallation baserad på en tidigare studie. Från resultaten och de restriktioner som fanns byggdes en tidslinje för tiden på Mars. Tillslut diskuterades icke-nominella scenarior för verksamheten på Mars.**

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I. INTRODUCTION

THE Red Planet is set to be the next milestone for human exploration, with private actors and governmental institutions setting the preliminary date for the first human on Mars in the late 2020s [1]. With the fast-paced development of space technologies, the design of a manned mission to Mars is now on the international agenda. To challenge humanity and push the limits of human exploration to the extremes of the solar system, the *Hephaestus project* assesses the feasibility of bringing the first human to the highest point of Mars Olympus Mons.

This paper is part of a larger 3-year mission design proposal to bring the first human to the top of Olympus Mons on Mars. The Mars manned mission is scheduled to bring six astronauts to Mars in 2039 for a total stay on the surface of 339 days. Four members of the crew will be brought from the landing site to the mountain, with only two of them performing the climb to complete the mission. The workload of the mission design process was distributed among five sections: general management, mission design, space vehicles, human aspects and Mars operations. This paper covers the section on Mars operations.

Some assumptions and constraints are given for the Mars mission. It is first assumed that by the time of the launch, several human missions will have been conducted on Mars. Three automated facilities are available on the Martian surface that allow for abundant resupply of water, oxygen and methane. To perform the climb, no flying vehicles are allowed over an altitude of 10 km below the summit. The last kilometre must be done by foot by at least one member of the crew.

To ensure success of the mission as well as crew and equipment integrity, operations on Mars must be precisely defined in the mission design process. Cooperation with the mission design and human aspects teams were significant to define the crew objectives and their safety throughout the mission and to eventually choose a general timeline for the operations on Mars. As part of Mars operations, means of transportation must also be carefully selected and therefore a continuous discussion with the space vehicle team was held to complete this work. Operations on Mars also require means of communication, with both Earth and between the different members of the crew.

II. Environment constraints for the mission

The red planet's environment is sufficiently harsh to add numerous constraints to the mission. When it comes to distance from the Sun, Mars is the fourth planet of our solar system. Smaller than Earth, it has a mean radius of 3389.5 km (0.532 of Earth's) [2]. With its mass of $6.42 \cdot 10^{23}$ kg (0.1 of Earth's), the gravity at the surface of the planet is 3.7 m/s^2. The atmosphere is very thin compared to the Earth's one. So the pressure at the surface of the planet stays quite low: 640 Pa (0.0064 bar). The density of the atmosphere can be described by an exponential decrease with a scale height of 11.1 km [2] and a surface density of 0.02 kg/m^3. A Martian day lasts 24.6 hours.

Mars's surface is not well protected from radiation either. Mars has no protective magnetosphere. The radiation levels are two to three times greater than at the International Space Station (ISS) [3]. Solar proton events can produce more than a hundred times higher doses than at ISS. The effective dose at the surface is estimated at 200 mSv/year. ESA does not recommend a total accumulated dose higher than 1000 mSv for the whole carrier of an astronaut. Because of this, sufficient shielding is required to conduct the mission on the surface. Shielding should be considered when selecting vehicles for the crew transportation on Mars.

The temperature at the Martian surface can vary from $-150°$ and $+20°$. Mars also has four seasons, but they do not last the same amount of time depending on the hemisphere. The difference of temperature between the poles can create strong storms. The dust stirred up can reduce the solar irradiance and decrease the efficiency of solar panels.

Olympus Mons is the largest volcano in the solar system with its 26.4 km height above the lowest point on Mars [4], which makes it around three times as high as Mount Everest on Earth. The summit of Olympus Mons is located on its south-east edge of the crater in the middle of the mountain as can be seen in Fig. 1. The volcano was created by lava slowly flowing down the sides of itself and has an average slope of 5° [5].

There are several constraints from the Management group, Mission Design, Space Vehicles and Human aspects. The management group requests that the summit shall be reached on a weekend, in order to maximise the number of people that can watch the journey. This will increase the advertisement price. The Mission Design groups decided that the stay on Mars will be 339 days, between August 25^{th} 2040 and July 30^{th} 2041. Because of the limited payload mass, Space Vehicles group requested that the payload to carry through the operations on Mars shall be minimised. Lastly, the Human Aspects group requires that the astronauts must take the time to regain some muscle and bone mass after they land on Mars. The teams decided together that Gusev Crater is the base that shall be used, since it is the closest to Olympus Mons.

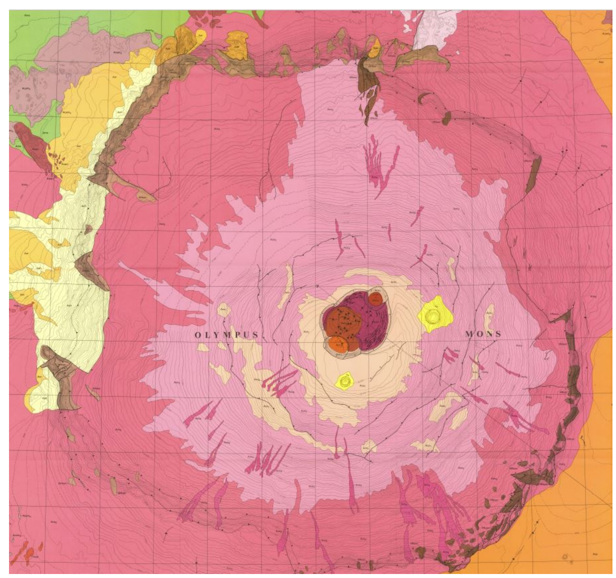

Fig. 1. Olympus Mons [4].

III. On-site Transportation

In this section means of transportation on Mars are discussed. With the Mars operations that were just described, the mission requires two types of vehicles: a space vehicle to travel between Gusev Crater and Olympus Mons and ground vehicles to go from the Hopper to the summit and back.

A. *Mars rover*

For the designed mission, surface mobility for the climb is essential. To explore the Martian surface with a roving exploration vehicle two options are considered: an unpressurised rover for a crew working in space suits, or a pressurised rover for the crew to work without a space suit. The first option has been used in the past with the Apollo program but excludes long excursions because of the restrictions imposed by space suits. However, in NASA's DRATS 14-day test in 2009 of a pressurised *Space Exploration Vehicle* on an environment similar to the moon, such pressurised rovers were found to significantly increase crew productivity [6] and were eventually selected for their relevance in a long exploration mission. The rover has to be designed to withstand the forces during launch from Earth while stored on its side. They have to be stored on their side to fit in the rocket, which is further discussed in Space Vehicle's group report.

1) Space Exploration Vehicle: The concept of the Space Exploration Vehicle (SEV) [7] developed by NASA is selected for Mars operations (see Fig. 2). The SEV surface concept has a pressurised cabin mounted on a wheeled chassis that would provide a living space for the astronauts during surface exploration missions on the Moon or Mars. It can also serve as a moving lab, which will be further discussed in the Research section.

The SEV has a docking hatch that would allow for efficient operations from the Hopper to the Martian surface. Another key aspect of this design is the suit port that allows the crew to quickly don the suits and makes the SEV suitable for a "*long excursion with multiple short spacewalks*" [7]. In this way, the SEV was found to be the manned rover concept most adapted to the requirements of the Hephaestus mission.

At this point in its development, the SEV meets the following requirements [7]:

- The pressurised cabin is design with a life support system that can hold a crew of two for 14 days [6]. It can also support a crew of four for 24 hours.
- Nominal speed is 10 km/h.
- The 12 wheels of the mobility chassis are able to pivot 360 degrees, allowing it to drive in any direction and manoeuvre over difficult terrain, which is to be expected on Olympus Mons.

The range is also a defining criteria in the rover selection process. It is limited by the distance astronauts can walk back to safe pressurised environment which is deemed by NASA to be 9.6 km (6 miles). The range can be improved by increasing the number of rovers for the excursion. If one rover was to break and could not be fixed, the SEV can sustain the four astronauts to drive back to the Hopper in time.

Assuming that the astronauts would walk at the optimal speed on Mars of 3.4 km/h [8] in case of an emergency and that the martian suits will have an autonomy of 8.5 hours by 2039, the range estimated by NASA of 201 km for two rovers can be increased to approximately 500 km with two SEVs which is within the mission requirements. Therefore, when designing the Mars operations the choice was made to bring two rovers from the Hopper to the top to have sufficient range to complete the mission.

Fig. 2. Space Exploration Vehicle Concept by NASA [7].

According to NASA, the SEV will rely on batteries for power supply. To this day, the development level of sufficient high energy density batteries was deemed too critical for a launch in 2039. Indeed, power required for such a mission was calculated to be very high compared to simple excursions missions for which the SEV was designed and called for a further discussion of power supply system for the rover.

2) Rover power supply: A rough calculation was made to estimate how much power the rovers will need to be able to drive 10 km/h. The required power was calculated as

$$P = v \cdot F_{friction} = \mu \cdot v \cdot mg \quad (1)$$

$$\Rightarrow 0.5 \cdot 10 \cdot 3000 \cdot 3.7 \approx 56\ kW, \quad (2)$$

where μ is the friction to the surface, v is the velocity and m is the mass of the rover. The friction to the ground is an approximate from previous research on the topic [9].

Regarding power for the rovers, two systems were considered. The first option discussed for powering the rovers is solar arrays. The second option is using fuel cells, which have been used during previous space missions, but are still under development. Calculations were made to assess whether these constraints could be met by either solar arrays or fuel cells.

Solar arrays

There are many benefits of using solar arrays as the power source; they are simple, do not require fuel and lightweight which have made them the choice for all rovers on Mars so far. A downside is that the rover can only be charged during the day as solar cells can only be used as a daytime power provider and it is more dangerous to drive at night, which means driving and charging both have to happen in the day. To investigate the feasibility of using solar arrays for the manned rovers, rough calculations are made. The efficiency of solar arrays have increased significantly for the past decades, from 4% in 1954 [10], to 29.5% in 2018 [11]. Since this mission is another two decades into the future, it can be expected that the efficiency increases further, 35% is used for this purpose. With the irradiance on Mars at 586.2 W/m^2 [2], the necessary area can be calculated with

$$P = \eta \cdot 586.2 \cdot A, \tag{3}$$

where η is the efficiency of the solar panels and A is the area of the solar panels. This would require an area of 270 m^2 per rover to drive 1 s for every second charged, or 68 m^2 to drive one second for every four seconds charged. It should also be noted that the batteries can only be changed during the day which would mean it is only possible to drive 2 hours per day when charging 8 hours per day. The range per day would then be 20 km. The biggest downside to using solar arrays would be that they could not get back to the Hopper within 24 hours of an emergency since the range is 20 km per day and at the top of the mountain they are 120 km away from the Hopper. Solar arrays were deemed unfeasible for the mission, especially when handling off-nominal scenarios that would require a mission abort to return to the Hopper. Moreover, dust accumulation and storms are concerning factors for the use of solar arrays for a long-term mission on Mars. Radiations could also damage solar cells and significantly reduce power output which would be detrimental for the rover.

Fuel Cells

To achieve better power-to-mass ratios fuel cells were considered to power the rover. According to literature, direct hydrogen cells have been shown to be the best option to power a mobile manned-laboratory similar to the SEV concept [12]. However the assumptions for the mission make it impossible to refuel with hydrogen at the base, which would increase launch mass and impair the future use of the rovers once the mission is over. The large quantities of carbon dioxide on Mars and the assumption of resupply in methane at the base supported the relevance of the use of another propellant for the fuel cells; methane.

Solid Oxide Fuel Cells (SOFC) is a type of fuel cell in which methane can be used directly as fuel [13], with a high-energy conversion efficiency. However, some development has to occur before it can be used in the rovers. The temperatures needed today are too high to make this method feasible, but some breakthroughs are being made in this field that would make this development achievable by the time of the launch [14].

Fuel consumption can then be approximately calculated from the energy density of methane. When methane is in its liquid form it has a volumetric density and gravimetric density of 6kWh/L and 14kWh/kg respectively [15]. The rovers drive a total distance of 250 km and this will take 25 hours. If 56 kW is needed to drive the rovers, 1388 kWh is needed for each rover, but 1500 kWh is used for safety. Given this data and assuming an efficiency of 80% [16], the fuel in volume and mass can be calculated as such

$$V = 1500kWh/0.8/6kWh/L = 312.5\ L \tag{4}$$

$$M = 1500kWh/0.8/14kWh/kg = 133.9\ kg \tag{5}$$

These results seem feasible for this project and SOFC driven by methane are therefore chosen as the main power source for the rovers. Solar panels, will nevertheless, be used on the rovers as a backup to fuel cells and be used to power the life supply system.

B. Hopper

In agreement with "Space Vehicle Group", it has been decided that the most efficient way to travel from Gusev Crater to Olympus Mons was using a flying space vehicle that will be called the ”Hopper”. The aim of such a vehicle is to provide a quick and safe way to travel between these two points, and to carry equipment needed for Life Support Systems and climbing. Moreover, a benefit of such flying vehicle is that the shape of the Martian surface between the base and the Mons have no impact on the trajectory.

For redundancy, it was decided to re-use the Descent Module on Martian surface to do the outbound and inbound flights to Olympus Mons. The Starship’s upper-stage is composed of three Raptor engines, providing an I_{sp} of 330 sec at sea level (380 sec on Mars) and a thrust of 2.2 MN each, leading to a structural mass of 108 tons. These powerful engines are the keys of the Hopper because the vehicle has to cover a ground distance of 3600 km, which is nearly impossible to reach with ground vehicles. Moreover, these engines are supported by a tank of propellant with a maximal capacity of 1200 tons of propellant. In addition to its engine properties, the benefits of reusing such a module is that a lot of things will already be included and will not represent heavier payload for the main rocket, such as heat shield, Life-Support Systems, altitude control commands etc.

The idea with this vehicle is to refill it at maximum capacity at Gusev Crater and use this propellant for both hops (goings to Olympus Mons and coming back to the base). In addition to its integrated Life-Support System, it will also carry the two rovers needed for the climbing mission and the part of the crew responsible of it, leading to a payload mass of 8.5 tons.

IV. TRAJECTORY

A few trajectories have been studied, taking into account different assumptions. These simulations had the goal of determining the ΔV cost of both hops.

The algorithmic simulations will not solve a Lagrangian optimising problem but will give rough numbers for ΔV and $m_{propellant}$ costs, which will be sufficient to discuss the feasibility of such trajectories. Indeed, many variables have to be taken into account to run an optimising algorithm which makes it hard to design and would be time costly, especially without insurance of success. Additionally, rough calculations are enough to choose the proper trajectory.

Moreover, the algorithms will first simulate the last hop i.e coming back to Gusev Crater. This seems logical because the amount of propellant needed for the first hop will depend on the cost of the second (mass of propellant for second hop is included in the payload of the first one).

A. Free-fall Trajectory

As a first simulation, a free-fall trajectory, like a cannonball, seemed to be a good approach to Mars’s dynamics. In this simulation, the propellant mass is the variable, and is changed in order to achieve the targeted range of 3200 km, taking into account the rotation of Mars. One hop was cut into different phases; first a vertical ascent, followed by a rotation with respect to the vertical angle α, thanks to altitude control thrusters and then a continuous thrust until the input propellant mass is fully consumed. Finally the gravity, in absence of thrust pulls the vehicle back to the ground.

This algorithm determines the vertical and horizontal components of the velocity, at each step of time that after integration leads to the position of the vehicle over time:

$$\begin{cases} V_x(t+1) = [V(t) + (\frac{T}{m} - \frac{D}{m})dt]\cos(\alpha), \\ V_z(t+1) = [V(t) + (\frac{T}{m} - \frac{D}{m})dt]\sin(\alpha) + \\ dt\frac{H(t)}{H(t)+R}, \\ V(t) = \sqrt{V_x(t)^2 + V_z(t)^2}, \end{cases}$$

where D is the drag of the vehicle, calculated at each steps of time because it depends on the norm of the velocity vector and on air density at its altitude. T is the thrust, R is the Mars radius and H is the altitude. The result of such simulation is given in Fig. 3.

According to this simulation, to achieve the targeted range, a total of 735 tons of propellant is needed. This amount is less than the total capacity of the Hopper but leads to important issues. First, this simulation only takes into account the inbound travel, which means that the outbound travel will cost more in propellant because the mass will be higher (must carry the fuel needed for the last hop). In addition, the ΔV cost of such trajectory is close to 3.5 km/s which leads to important landing issues. Because of the lack of atmosphere, systems which increase drag (such as parachutes) can’t be used

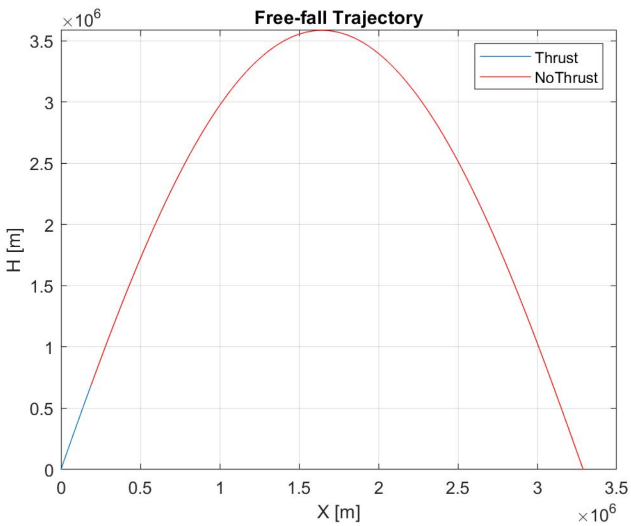

Fig. 3. Free-fall Trajectory for the second hop.

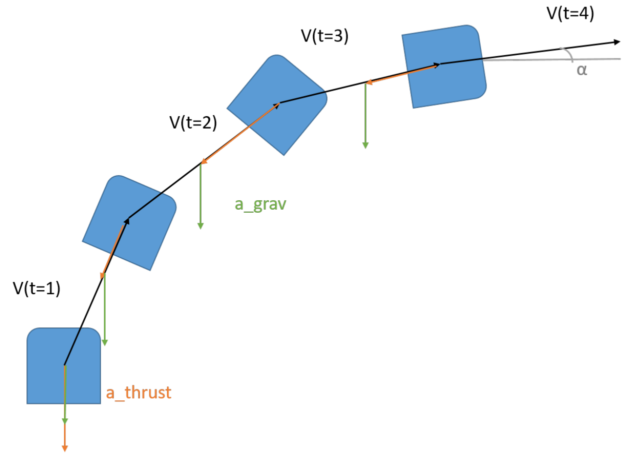

Fig. 4. Gravity Turn Trajectory.

and the vehicle has to slow down by thrusting in the opposite direction of the movement: this has an approximate cost of propellant of 200 tons, which in total exceeds the capacity of the propellant tank. It is also higher for the first hop because mass will be higher.

In addition, some assumptions have been made that have to be corrected with further analysis, especially regarding the oblateness of Mars. In this free-fall simulation, Martian ground is assumed to be flat but regarding the distances that have to be reached, this assumption is no longer valid.

B. Gravity Turn

Taking the oblateness of Mars into account leads to consideration of a trajectory helped by a gravity turn. This phenomena is a manoeuvre that uses gravity to steer the vehicle into a targeted orbit (see Fig. 4). Thanks to Mars attraction, the costs of the travel is reduced compared to the first simulation.

The gravity turn is based on a mathematical law giving the evolution of the angle between the horizontal and the velocity vector over time:

$$\dot{\alpha} = -\frac{1}{V}(g - \frac{V^2}{R+H})cos(\alpha) \qquad (6)$$

The scenario of this trajectory is close the previous one. First, the Hopper is launched vertically during a few seconds, and then a little angle is given while thrusting. Thanks to this little change, $\dot{\alpha}$ is non-zero and the gravity turn starts, rotating the Hopper over time. Thanks to a change in angle, the Hopper can catch an elliptical trajectory (where the center of Mars is one of the focuses) which intersects the ground at the landing site on Olympus Mons.

Many simulations were made with this scenario, leading to non conclusive results because all of the fuel was consumed too fast and the Hopper landed long before Olympus Mons.

After this, a new scenario was constructed where thrust is provided with parsimony, igniting a certain number of Raptor engines depending on the angle α. This criteria is purely quantitative and would also be a variable of the Lagrange optimising algorithm if it would be coded (making it even more complex). This allows the Hopper to stay in the range of action of gravity and to reach important distances. A trajectory for a given variation of thrust over time is given in Fig. 5.

The first difference compared to free-fall trajectory is the maximal achieved height, lower for the gravity turn trajectory. This is logical because the Hopper stays at an altitude where the gravity has an impact, and the travel is horizontal with respect to the ground (and not with a bell trajectory compared to the previous simulation).

With this simulation, a propellant mass cost of 695 tons is estimated, corresponding to a reduction of 5.4 % of propellant mass compared to free-fall. By also taking into account the mass needed to land, the propellant tank seems well-dimensioned for the return travel, but still won't achieve both travels without refilling. However this simulation is really sensitive and a little change in parameters can crash the Hopper or hugely reduce its range.

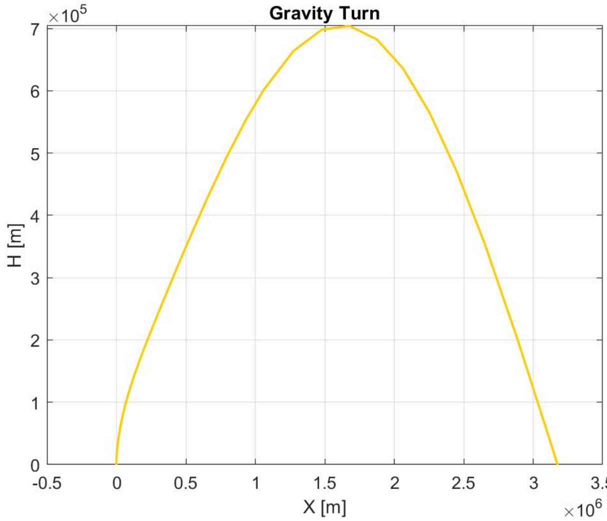

Fig. 5. Gravity Turn Trajectory for the second hop.

Because of the assumption of discontinuous thrust along the movement many parameters characterise the flight, such as the value of the change in angle after the vertical launch, the propellant mass and the angle at which the engines are reignited. Furthermore, aspects such as at which thrust and for how long it takes place makes it hard to optimise (high sensitivity to inputs). However, it is interesting to highlight the huge impact of gravity on propellant mass. This method could be a very good way to model the real travel with more accurate data and with optimisation. Because of this, it has been decided to go with another, easier simulation that consists of following the ellipse mentioned before, directly from the launching site.

C. Elliptic Trajectory

By controlling the thrust at each point of the trajectory, the gravity turn method can be optimised to reduce the amount of propellant. At the end of take-off, when thrust is zero, the Hopper is in free fall. As Mars's atmosphere is very thin, we can consider that during free fall the Hopper will follow an elliptical orbit as predicted by Kepler's first law. A good approximation of the final trajectory (taking into account take-off and landing) is then a simple ellipse. A discussion on how to follow the ellipse during take-off is done later.

Several ellipses are acceptable to do the hop. They all have a semi-major axis lower than the Mars' radius and their points of focus is at the centre of the planet. They intersects the planet surface at the take-off site. However, the rotation of the planet has to be taken into account. The ground distance between Gusev Crater and Olympus Mons is 3600 km (see Fig. 6). During the flight, the rotation of Mars will bring the landing site closer or further away. However, the amount of fuel needed to do the hop only depends on the altitude and not the ground distance. The rotation of Mars also influences the take-off and landing phase. Landing or taking-off in the direction of the planet's rotation is easier.

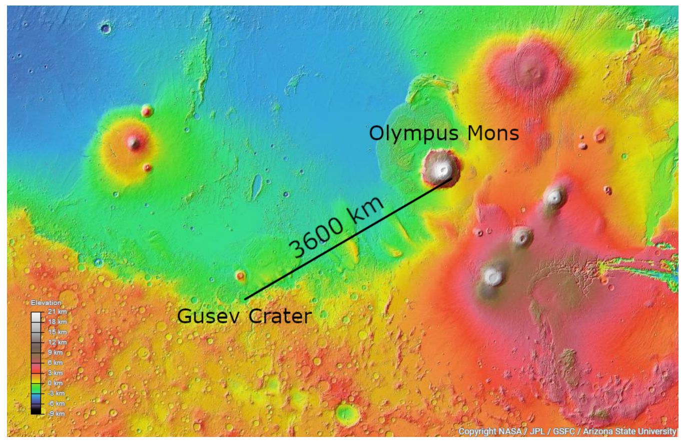

Fig. 6. Representation of the ground path.

The chosen trajectory (represented in Fig. 7) has a maximum altitude of 600 km. By assuming no drag, the difference of speed ΔV needed to take-off and follow this trajectory is $\Delta V = 3.2$ km/s for the Gusev Crater→Olympus Mons trip and $\Delta V = 2.8$ km/s for the Olympus Mons→Gusev Crater one.

The rotation of the Hopper using the gravity turn is quite slow due to the power of the engines combined with the low gravity of Mars. However, following the elliptical trajectory requires a high inclination after take-off. Such inclination can be achieved with a simple gravity turn by having a low thrust for a long time. The attitude control system of the Hopper can also be used to increase the rotation speed. A simulator has been developed to estimate the influence of the drag on the fuel consumption during take-off. This simulation assumes that the Hopper can freely rotate the direction of thrust and that the Hopper always tries to follow the elliptical path. Due to the low thickness of the Martian atmosphere the fuel mass needed to take-off does not vary a lot with or without the assumption of air drag.

Gusev crater has an altitude of 2 km. This low

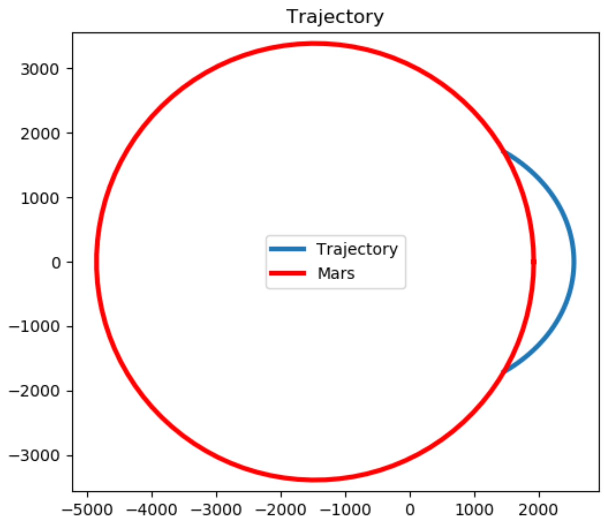

Fig. 7. Elliptical trajectory with a maximum altitude of 600 km.

altitude increases the thickness of atmosphere that needs to be penetrated in order to reach the landing site. A method to land has been designed by SpaceX using the air drag to strongly decrease the speed of the spacecraft. It is presented in the Space Vehicles report. The ΔV needed to land is then reduced to 500 m/s. However, the landing site at Olympus Mons is located at an altitude of 16.4 km. At such altitude, the atmosphere density is too low to permit a strong deceleration using air drag. The maximum ΔV is obtained by assuming no drag. It is then 2.8 km/s. Some methods to reduce this ΔV can be designed. One example is to use the fact that the mountain is very steep. You can then descend below 16.4 km altitude, which reduces the arrival speed. Then use the remaining speed to climb back above 16.4 km/s in an aircraft-like fashion. Such climbing is used to reduce the speed in the method presented in the report by the group working on Space Vehicles. The remaining ΔV is then well below the initial ΔV of 2.8 km/s (around 1.5 or 2 km/s). However, more complex simulations have to be done in order to determine such a landing.

Both take-offs need a total ΔV of 6 km/s. The final landing at Gusev needs a ΔV of 0.5 km/s. The Hopper presented in section III-B has a ΔV available of 8.8 km/s. The landing at Olympus Mons needs a maximum ΔV of 2.8 km/s. The maximum ΔV is then 9.3 km/s. With future propulsion technologies or a better landing method, this ΔV can match with the ΔV available.

The time needed to do the hop is difficult to compute exactly. However, both trip will last less than 35 min. The rotation of the planet will move the targeted landing site from at most 400 km.

V. Communication

Reliable communication is one of the largest challenges humans face when travelling to Mars. This includes communication between Earth and Mars, but also has to include a reliable system for a Martian base, which enables astronauts to communicate on the Martian surface when they are split up.

Mars is particularly difficult since the geometry of the orbits make it almost impossible to communicate when Earth and Mars are in conjunction (opposite sides of the Sun). The distance is then roughly 2.5 A.U. (1 A.U. = 149.56 million km), however the main problem is not the distance but the Sun's radio interference. Furthermore, direct communication with Earth is not possible during the solar night on Mars, since the planet itself is blocking the way to Earth for a base on the surface. Even though the signal loss is not completely in sync with the nighttime, it will be assumed so from here on, since it is a very good approximation.

For current rovers on the Martian surface (specifically Curiosity and Perseverance), the solution is to send data to an orbiter around Mars. Today the orbiters can ”see” the Earth around 2/3 of each orbit, which enables more data to be transferred per Martian sol than with a direct transfer. Additionally, since the orbiters are able to produce a lot more power and have larger antennas compared to the rovers on Mars, these can thus transfer more data [17]. The same principle is used to solve the communication for a Martian base, however this time with more orbiters to allow less downtime in terms of signal loss.

The solution is based on the Monarch Project [18], which is a mission that consists of launching satellites into Martian orbits, providing reliable communication between Earth and a base anywhere on the surface. Furthermore, one of the key requirements for early (or all) exploration missions to Mars is that all technologies need to be robust, without ”single-fault failure” systems. The Monarch project specifically puts a lot of emphasis on robustness and safety, which is why it fits very well with the requirements of this mission. The satellites are assumed to be launched and placed in orbit before the main mission to climb Olympus Mons is taking place, and since the total constellation weighs around one metric ton, there is a high probability of riding piggyback on a rocket. For each satellite, a mass of around 7 kg is left over to be utilised. Since they are not equipped with hardware for a GPS system to begin with, they will be upgraded with the addition of atomic clocks. Very accurate atomic clocks have been demonstrated with a weight as low as 35 grams [19]. Therefore, these are assumed to fit within the 7 kg limit even with adaption to the space environment. This will allow more accurate time calculations, and thus by calculating the time it takes for a signal to be sent from three different satellites to a rover or an astronaut, the position can be triangulated and be used as navigation [20].

For the satellites in orbit, the constellation is a Walker-Delta 55:10/2/1, which means at 55° inclination from the Martian equator 10 satellites are evenly spread out in 2 different planes. In each orbital plane, the satellites are placed at 120° of each other, in combination with being phased 60° between the planes. The altitude is 17030 km, resulting in an aerosynchronous orbit [21]. As can be seen in Fig. 8 the orbits are designed to be circular for simplicity. With this constellation, global

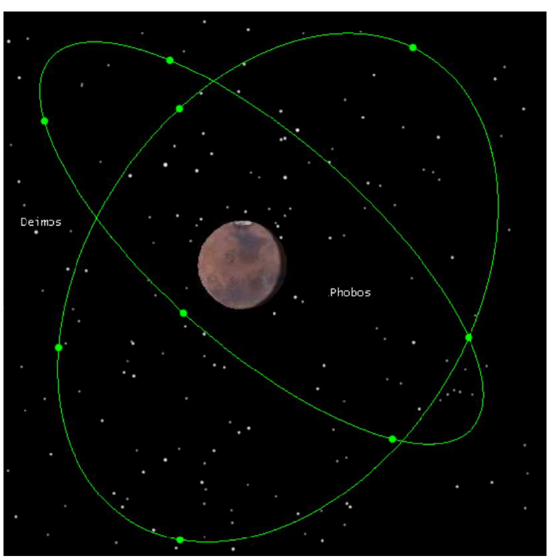

Fig. 8. Walker-Delta 55:10/2/1 constellation [18].

coverage is assured with no loss of coverage with up to two satellites removed, again putting emphasis on robustness. With a third satellite removed, the probability is still roughly 93% that global coverage is achieved, as verified by simulation in the project report [18]. The satellites are designed to last at least 36 months in a Martian orbit, and therefore they satisfy the needs for this mission well within limits.

While the delay caused by the speed of light limits communication to between roughly 3 and 21 minutes, the delay time for a message to be sent internally is a matter of seconds. Therefore, the internal delay times does not have a large impact on the total transfer time of a message. For the Monarch constellation, a more robust protocol is used called a Cascade Relay Scheme (CRS) [18], which sacrifices some time and bandwidth for robustness. It is therefore less inefficient than an addressing scheme, however with the focus on robustness it has safety advantages. In the spring report cited a full description of how the algorithm works can be found. For this report, an internal lag time of around 11 seconds is accounted for, with CPU processing time included, which has been verified via analysis [18].

When it comes to the data throughput, it is calculated as

$$D = \frac{N_p d_{payload}}{t_{trans}} = \frac{135 \cdot 2048 \text{ b}}{1.991 \text{ s}} = 138.9 \text{ kb/s}, \quad (7)$$

where N_p corresponds to the number of packets per message, $d_{payload}$ is the number of bits per packet and t_{trans} is the time for transmitting a message for one satellite. N_P and t_{trans} were iterated from Equation (2) in [18], and the payload is decided by the packetization format which is well described in the report cited. As a reference, the Curiosity rover can send 128 kb/s or 256 kb/s to the Odyssey orbiter today, which is between around 4-8 times faster than a home modem [17]. It is however important to note that with the few satellites in orbit today, the rover can only send data to the orbiter for about eight minutes per sol, which in fact leads to a much lower total amount of data transferred in comparison with the Monarch system that comprises 10 satellites.

VI. Research

After the climbing of Olympus Mons, there are around 200 days on Mars for doing research and maintaining systems. The research will be done partly to entertain the crew during this time, but also to utilise the time they have on Mars for science and to fund the trip. The mission will take place quite far in the future and therefore it is difficult to know what findings rovers and spacecraft have made until then. However, some goals and examples of research can still be presented.

The general goals of the research on Mars consists of determining if life existed on Mars, characterising the geology of the planet and preparing for future human exploration of Mars. The climate is also a subject of interest, and some experiments which were not able to be performed by robots or spacecraft can be conducted by the human astronauts.

For the first goal, finding liquid water is of course of vital importance. While this has been researched already using both spacecraft and rovers on the surface, drilling is not easy since they can get stuck easily, which is what happened with Curiosity's drill [22]. Therefore, humans can help with drilling deeper into interesting parts of the Martian surface.

For characterising the geology of Mars, samples from different parts of Olympus Mons can be taken and studied by the entire crew, but especially the astrobiologist. NASA's concept for the SEV can furthermore be used as a lab, which makes the research simpler to execute. The crew can make smaller excursions during the time after mounting Olympus Mons, and studying the samples as they go.

While some aspects regarding the hostility of Mars has been investigated already, there are a lot of unknown parameters to further examine. One of these aspects that the astronauts will get exposed to is radiation and UV rays, since Mars lacks a magnetic field and an ozone layer. Therefore human aspects can be examined and be used to pave the way for future human missions to Mars.

VII. Results: Operations timeline

Arrival on Mars and acclimatization

Day 341 of the mission is the day the astronauts will land on Mars. They will land as close to the base on Gusev Crater as possible while keeping a distance as not to harm the equipment on ground with high velocity sand blasting. When the astronauts have landed on Mars they have five months of a rigorous work-out routine ahead of them. This is to gain back some of the muscle and bone mass that they have lost on the journey in zero gravity. Since Mars has less gravity than Earth, the astronauts do not have to get back to their original fitness level, just enough to be fit and strong on Mars. During these five months, the Hoppers and rovers have to be fuelled to prepare for the hop that will happen on day 493. Since the fuel that will be needed is in the order of 100 tons per Hopper, the fuelling has to start soon after touch down.

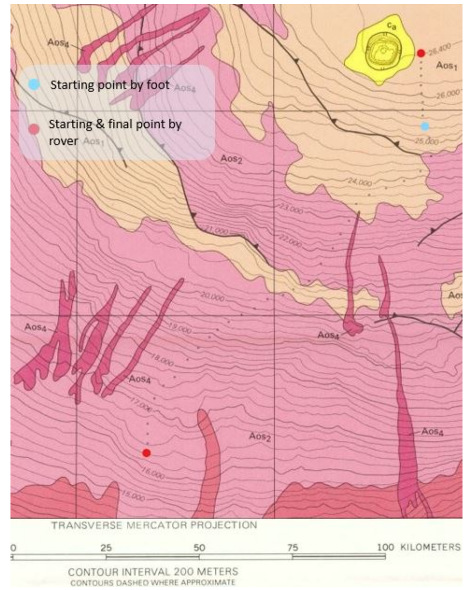

Fig. 9. Suggested route on Olympus Mons: from landing site of the Hopper to summit [4].

The hop to Olympus Mons

Shortly before the hop to Olympus Mons, the Hopper and rovers have to be prepared. There is a lot of equipment to be brought, such as spare parts, shovels, medical equipment, camera, GPS and radar. Only four out of the six crew members are going to Olympus Mons, the four selected people are the Commander/Mechanical engineer, the Spaceship Pilot/Mechanical engineer, Mission Specialist 1/Electrical engineer, and the tourist. The engineers are chosen since they are the best fit to ensure that the rovers can be repaired if they break down. The tourist is there to help fund the trip, but is expected to assist the engineers if need be. The other two crew members, Mission Specialist 2/Medical Expert and Mission Specialist 3/Astrobiologist stay at Gusev Crater to perform research and be prepared to assist the mounting team if needed, discussed further in section VIII.

Landing and driving

The astronauts land 10 km below the top according to the requirements, this corresponds to an altitude of 16,400 m on Mars. This landing site is shown as the lower red dot in Fig. 9. When they have landed, the astronauts get in the two rovers and start driving. Since the hop only takes 35 minutes to do, the astronauts will do this in the morning, to have time to start driving the same day. It is assumed the rovers can drive 10 km/h even at a 5° slope. The total drive to the point that they then have to walk from is approximately 120 km [4], which is split into two days. This is to have some margin to solve possible problems and to charge the solar panels to power the life supply.

Walking to the summit

On the end of day 494 they will arrive to the -1 km point, shown as the blue dot in Fig. 9. Two of the four people going to Olympus Mons will attempt mounting by foot, the commander and the tourist. The other two drive the rovers and assist in case of an emergency. They are then well rested and can step in. Since the commander and the tourist are being followed by the rovers, they only have to carry the absolute necessities; oxygen, water and carbon dioxide filters. The distance from the -1 km point to the summit is around 25 km [4], assuming the commander and tourist walk an average of 3 km/h it will take eight hours just to get to the summit. They can therefore not get to the summit and back to the rover in one day. The rovers following them for safety will also be used to sleep in after they have reached the summit and to refill oxygen tanks, water supply, and carbon dioxide filters. The schedule will be made to optimise the time of getting to the summit to make sure it is at a time of day so that as many people as possible can follow the announcement from Earth. It will also be on a Saturday, the 26^{th} of January 2041, to further optimise the advertisement possibilities.

Journey back to the Hopper

After the mounting has happened and all the pictures, samples and videos have been taken, the astronauts will walk back down to the -1 km point and the next two days, day 497 and 498 will be spent driving back to the Hopper. From there, they will hop back to Gusev Crater and bring just one rover. The other rover is left on the mountain to minimise the payload mass for the second hop. It will be as sealed off as possible to minimise contamination of Mars.

Back at the base

The time of roughly 200 days from they get back to Gusev Crater to lift-off from Mars will be spent doing science and explore the nearby surroundings. This is further discussed in section VI. Since there is only one rover left, they will not be able to get far. This is for safety reasons, if a rover breaks they must be able to walk back to the base.

The total time on Olympus Mons for a nominal mission is 6 days, but the rovers have 14 days of life supplies. This is to make sure they still have enough time for mounting even if there are issues, such as a rover failure or if the rovers get stuck in the sand. The off-nominal scenarios will be further discussed in section VIII.

VIII. Off-nominal scenarios

There are many scenarios that could happen on Mars and lead to mission failure. Two main scenarios were considered in the mission design process for operations on Mars. The first one concerns the possibility of having the Hopper breaking on Olympus Mons and the other is the scenario in which one of the rovers breaks or has to be abandoned on the mountain.

Should the Hopper break, the two astronauts left in Gusev Crater will use the other Hopper to hop to the mountain and get them back. To make sure they will get there before the life support runs out, both Hoppers will be fuelled at the base before the astronauts go to Olympus Mons. This possibility was discussed throughout the progress of the project with the other groups, especially with the *mission design* and *space vehicles* groups.

The second scenario was continuously discussed during the definition of the Mars operations timeline. As a first consequence of that as well as for the reasons previously stated in 2, two rovers are used during the climb. With the SEV as vehicle, the life support system of one rover is sufficient to bring back all the member of the crew climbing the mountain in case one rover breaks to the point that it cannot be repaired in a reasonable amount of time. For that reason solar arrays were abandoned as a primary power supply system, as they were calculated to not allow sufficient autonomy for an abort of the mission and return to the Hopper in less than 24 hours. As mentioned in the Mission Design report, out of the four people going to Olympus Mons, two of them are mechanical engineers and one of them is an electrical engineer. They are specialists in the SEV's to mitigate the risk of the rovers breaking down without the possibility to repair them. If they, indeed, break down, the astronauts have 14 days of life support and the mission should only take six days. This is to make sure they can make necessary repairs or get the rover loose if it gets stuck.

Failure in communication is a serious off-nominal scenario that could end catastrophically. Therefore robustness has had the highest priority when choosing a communications system, and as already explained in section V two satellites can break or be lost without any loss of coverage on the surface of Mars. If more satellites would fail, communication would still be possible but with a lower probability of coverage and less amount of time for data transfer, since orbiters won't be visible to the Martian base as often. However, vital communication such as talks between astronauts would still be feasible.

IX. Conclusions

Using the descent vehicle as the Hopper and NASA's conceptual design will get the astronauts to and from Olympus Mons safely. Having the rovers powered by fuel cells is the most efficient way to travel for these distances in the given time of life support in the rovers. Using ten satellites in a Walker-Delta constellation is a feasible solution for communication on the Martian surface, providing global coverage. These can furthermore be used with atomic clocks for navigation. The mission on Olympus Mons will take less than two weeks, but staying on Mars for a prolonged period of time assures there will be time for mounting without endangering the mission through illness, or breakdowns of systems. Having an extended stay on Mars naturally raises the risk for health issues, system issues or other problems that can arise. However, since the astronauts are so well prepared, they will be able to fix problems as they come along.

X. Workload breakdown

A. Julie Meunier

Julie worked on the rover selection process as well as their power supply systems with Elina. She performed estimations of the mass of propellant needed and other calculations regarding the mission timeline and off-nominal scenarios. She wrote section I, III-A and contributed to the sections VIII and III-A2.

B. Elina Arvidsson

Elina mostly worked on the rovers with Julie and its power supply with Julie and Gabriel and wrote section III-A2. She also worked on and wrote sections VI, VII, VIII, IX.

C. Gabriel Kronberg

Gabriel has mainly worked on figuring out how the communication on Mars will proceed. Furthermore, he assisted Elina and Julie in determining an appropriate system for powering the rovers. In the report Gabriel wrote section V and contributed to sections VI, VIII and IX.

D. Tanguy Pollastro & Marc Pierre

Tanguy and Marc worked on the data for the Hopper with the Space Vehicles Group and the trajectories between the base and Olympus Mons. They performed free-fall, gravity turn and elliptical trajectories, algorithms and calculations. Tanguy wrote the section IV-A/B. Marc wrote section IV-C and section II.

E. Team

The whole team worked together (and with the other groups) on the choice of the base, crew size and selection of crew. Logistics decisions for the ascent of Olympus Mons were also made by the group.

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