IAC-12-IAC-22, A5, 4-D2.8,4

MISSION TO MARS USING SPACE-SOURCED PROPELLANT

J. Thoemel,
Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg,
jan.thoemel@uni.lu

M. Ludwikowski[1], P. Karakatsanis[1], R. Zong [1], R. Weber[1], R. Schmidt[1,2], A. Hein[1]
[1] Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg
[2] European Space Agency (ret.)

Current on-going efforts to source materials in space for their use in space will enable more cost-efficient and more versatile missions. It is consensus that the first application to this end will be to use propellant stored or even produced in space.

We study the impact and potential of sourcing propellant at two different locations, that is, from depots in a lunar orbit and the farther Sun-Earth-Lagrangian point 2.

To this end, we conduct a high-fidelity analysis for a mission to Mars using the General Mission Analysis Tool modelling all major mission arcs and propulsive events. We started with a pilot study where we compared our method to the 2003 MarsExpress mission, which serves us as reference. Then, we simulate missions for the 2026, 2028, 2030 departure windows. We compare the potential payload increase and the permissible launcher performance reduction.

We find that, even if considering a mass reservation for refuelling equipment, the payload mass can be substantially increased and, in addition, a smaller, hence more cost-efficient launcher can be employed for both scenarios. The use of propellant obtained from in-space propellant depots is promising and suggests the conducting of such mission.

I. INTRODUCTION: THE EXPENSIVE JOURNEY TO MARS

Missions to Mars remain among the most difficult space missions we conduct. The need for high-technology solutions, the high overall risk in spaceflight, the infrequent departure windows to Mars approximately every two years, and the need for very speeds, hence large amount of propellant, to reach the destination make it also one of the most expensive missions.

While technology matures and become cheaper, and risks become lower with experience, the physics dictate the latter two remain obstacles.

In contrast to most missions to low earth orbit (LEO), interplanetary missions, such as missions to Mars, require large amounts of propellant for instance for orbital maneuvers, such as orbit injection maneuvers. The mass of the needed propellant can dominate the spacecraft overall mass and can hence be mission design driving.

Thus, ideas were developed [1] addressing how to reach Mars more flexibly and at a lower cost. Propellant depots, where spacecraft can refill their propellant tank and park until a suitable instant in time can solve both challenges. This article reports results of our research regarding the use of propellant sourced and stored in depots located in space. We research how the use of propellant obtained such depots can enhance missions. As reference, we take the Mars Express mission launched in the year 2003 by the European Space Agency.

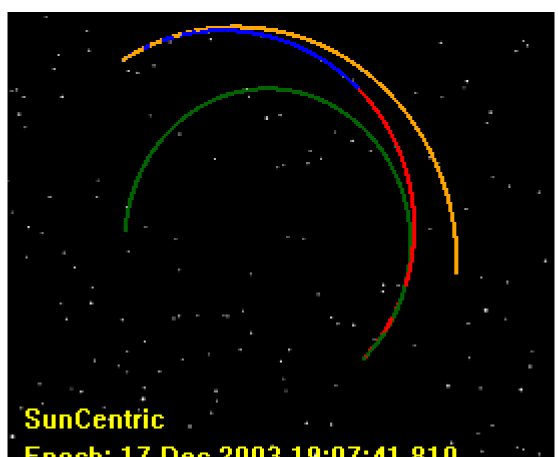

Figure 1 Mars Express-like trajectory from Earth to Mars during departure window 2003 simulated with GMAT. The Sun is in the centre, Mars and Earth orbit the Sun. The blue-red line indicated the trajectory of our Mars Express-like mission.

It featured a modified commercial satellite bus, an in-orbit payload to observe the planetary surface and a lander payload called Beagle 2.

Table 1: Mass budget Mars Express

component	mass [kg]
satellite bus	439
launch adapter	170
refuelling equipment	0
total system	**609**
on-orbit payload	116
lander payload	71
total payload	**187**
propellant	427
GRAND TOTAL	**1,223**

Our high-level reference mass budget is given in Table 2. Mars Express was exceptionally successful in its fast development implementation and scientific operations still acquiring scientific data at the time of writing of this article.

II. CHALLENGE: REDUCE MISSION COST THROUGH USE OF SPACE-SOURCED PROPELLANT

A mission making use of propellant obtained at propellant depots can benefit in two ways:

A. reduction in loaded propellant at lift-off
B. reduction of speed, or characteristic energy, C3, due to the relative proximity of the depot location compared to the destination.

This allows three approaches on how to improve missions; we name and characterize them as follows:

1) **launcher minimum:** reduction of loaded propellant at lift-off. This allows the use of a drastically smaller launcher.
2) **mission optimum:** reduction of loaded propellant and increase of payload mass until total spacecraft mass is matched to reference spacecraft mass. This approach allows an increase payload and a smaller launcher.
3) **payload maximum:** reduction of loaded propellant and increase of payload mass until performance of reference launcher is matched. This allows a drastically larger payload.

Our research interest is in understanding how a Mars Express-like missions can be improved without extremely deviating from the original concept. Thus, our research addresses the second option.

We investigate the increase in payload mass and reduction in launch performance for two propellant depot locations:

i. lunar orbit
ii. Sun-Earth-Lagrangian point 2

The use of propellant depots can improve missions also in further ways. For instance, a launch is dependent on the weather at the launch site. This obliges mission designers to consider non-optimal launch dates and thus trajectories to the destination and consequently additional propellant at lift-off. A mission through a refuelling step can launch well ahead of the optimal interplanetary to-destination-departure instance and wait at the depot for the optimal instant in time for the interplanetary mission arc. The departure from the depot does not depend on such unforeseeable circumstances.

Missions through propellant depots also have disadvantages. The need for docking and refilling technology increase complexity and mass of the spacecraft and fidelity of the mission. Also, the type and cost of the space-sourced propellant needs to be accounted for.

III. METHOD: SOFTWARE USED AND ITS MATH

General Mission Analysis Tool (GMAT)

To investigate the benefits of missions that refill their tanks on the way towards their destination, we use NASA's General Mission Analysis Tool (GMAT) in its 2020a version. It is a high-fidelity trajectory analysis tool with a convenient Graphical User Interface and accessible scripting feature.

For calculating trajectories, we employ the built-in Prince-Dormand 78 propagator. It needs adequate initial conditions, which we obtain through NASA Trajectory Browser[2] website.

As there is no need to model the actual launch from the surface of the Earth, we start our simulations with an initial elliptical orbit from which we derive the needed characteristic energy, C3.

The uptake of space-sourced propellant is time consuming due to the process and the additional to and from the location of the space depot and is thus of primary interest for robotic missions where, in contrast to human missions, a longer exposure the space environment is acceptable. Therefore, in the following, we focus on optimizing, *i.e.*, minimizing the propellant consumption for the in-space maneuvers in the mission study over launcher performance or time-of-travel.

We thus iterate to compute optimal trajectories with the least amount of propellant consumption for maneuvers by varying key parameters using the built-in Yukon optimizer.

The maneuvers are assumed to be instantaneous – a reasonable assumption for high thrust propulsion events in interplanetary missions; hence we model them as infinite impulses.

In our subsequent mission analyses, we reserve 50 kg for the docking and refilling equipment and assume the availability of a common storable propellant with an I_{sp}=320 s.

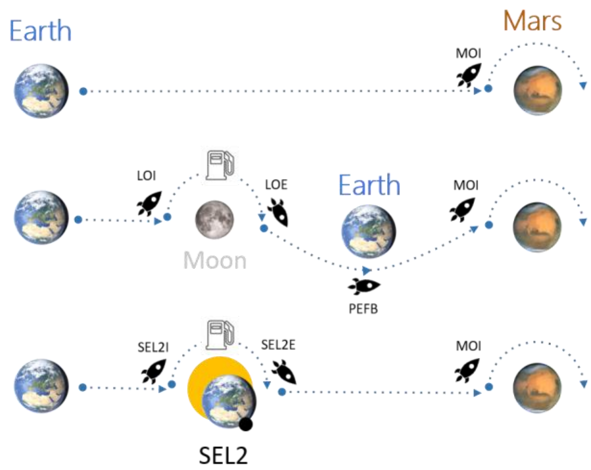

Figure 2 Mission overview (SEL2: Sun Earth Lagrange point 2, MOI: Mars orbit injection, LOI: lunar orbit injection, LOE: lunar orbit exit, PEFB: Power Earth Fly-By, SEL2I: SEL2 injection, SEL2E: SEL2 exit).

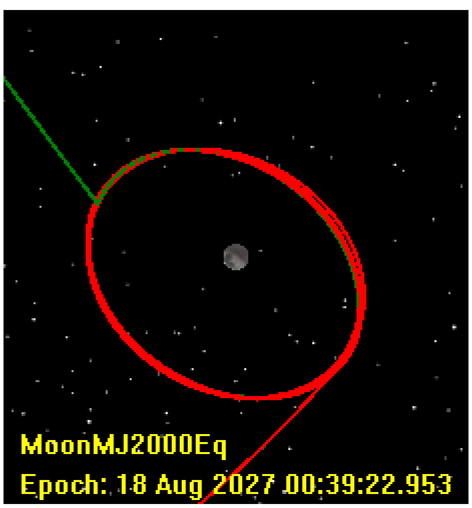

Figure 3 Trajectory towards, following and departing lunar propellant depot (Moon-centric view).

We assume that no propellant margin is needed for the mission arc towards the depot following the rationale laid out above, *i.e.* that the toward-depot journey can be done with an optimal weather independent trajectory. We also assume that 50 kg propellant reserve is needed after the arrival on Mars for the science operations.

Table 2: Overview of simulated missions.

ID	path	maneuvers
D03	Earth-Mars direct/Mars Express-like	MOI
D26	Earth-Mars direct	MOI
D28	Earth-Mars direct	MOI
D30	Earth-Mars direct	MOI
M26	Earth-lunar orbit-Mars	arc 1: LOI arc 2: LOE, PEFB, MOI
M28	Earth-lunar orbit-Mars	arc 1: LOI arc 2: LOE, PEFB, MOI
M30	Earth-lunar orbit-Mars	arc 1: LOI arc 2: LOE, PEFB, MOI
L26	Earth-SEL2-Mars	arc 1: SEL2I arc 2: SELOE, PEFB, MOI
L28	Earth-SEL2-Mars	arc 1: SEL2I arc 2: SEL2E, MOI
L30	Earth-SEL2-Mars	arc 1: SEL2I arc 2: SEL2E, MOI

Overview of Simulated Missions

The missions we simulated are described in Figure 2 and listed in Table 2.

We carried out a simulation campaign for the Mars departure windows 2026, 2028 and 2030 for the direct to Mars mission, a refuelling mission concept for depot in lunar orbit and a for a depot location in the Sun Earth Lagrangian point 2. Simulating several departure windows allows obtaining limited statistical data and understanding of the uncertainty and credibility of our results.

IV. RESULTS: TRAJECTORIES TO MARS

Pilot Study

We conducted an initial study[4] validating our method. The obtained the Earth to Mars trajectory as shown in Figure 1. We compute a launch date of 2nd June 2003 coinciding with the actual launch date, but an arrival date of 17 December 2003 deviating from the actual arrival date by eight days (4% of time-of-travel), and a relatively high characteristic energy of 22.1 km^2/s^2. We see our method confirmed and attribute the differences to more complex requirements, *i.e.* optimization cost function, of the trajectory of the actual Mars Express mission.

Mission studies departure windows 2026/2028/2030

Direct

For each departure window, we simulated the direct mission, which served then as reference for the comparison for the refill-mission simulations.

Lunar Orbit Depot

Then, we simulated the mission to Mars with a refill stop at the lunar propellant depot location, *i.e.* a 20,000 km altitude-near-equatorial-lunar orbit.

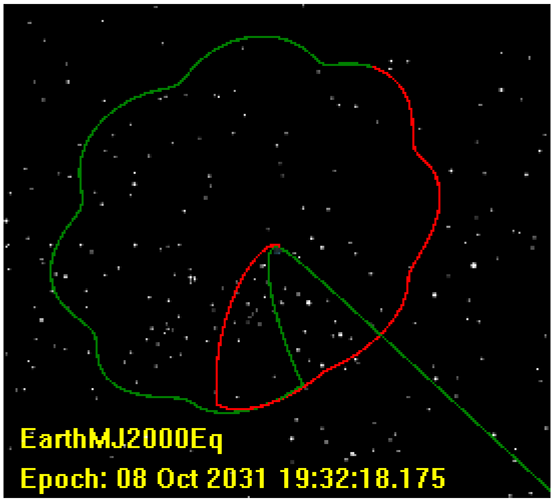

Figure 4 Trajectory towards, following and departing lunar propellant depot (Earth-centric view).

The trajectory towards the lunar orbit, of the lunar orbit and its departure arc towards Mars is shown in the lunar coordinate frame in Figure 3 and in the Earth centric frame in Figure 4.

The figure also shows, how we simulate the towards-Mars mission arc. It is conducted with an Earth-flyby, which significantly reduces the needed propellant.

Sun-Earth-Lagrangian Point 2 Depot

Then, we simulate missions for a depot location presumed at the Sun-Earth-Lagrangian point 2 (SEL2).

An example of the SEL2 orbit is given in Figure 5.

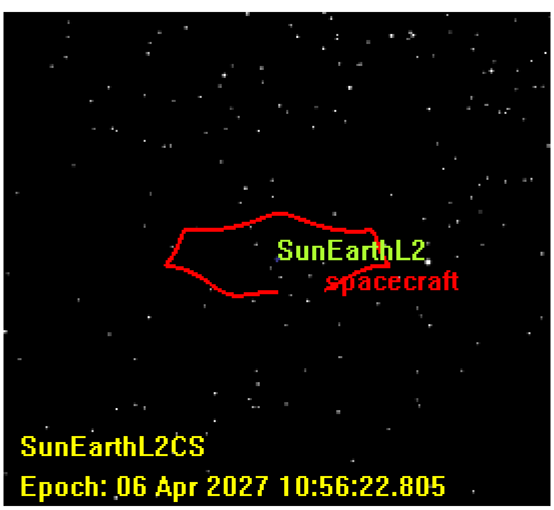

Figure 5 Propellant depot location Sun-Earth-Lagrangian point 2.

Since the SEL2 does not present a gravity well, no orbit injection maneuver is required. The magnitude of the exit maneuver is only determined by needed energy to reach Mars. Unfortunately, our optimization method did not find a suitable trajectory with an Earth or Moon-flyby as we found for the lunar orbit depot location simulations. This results in a propellant excess not present otherwise.

Each of our simulations is concluded in an elliptical orbit around Mars resembling Mars Express' arrival orbit. Such orbit is exemplified in Figure 6.

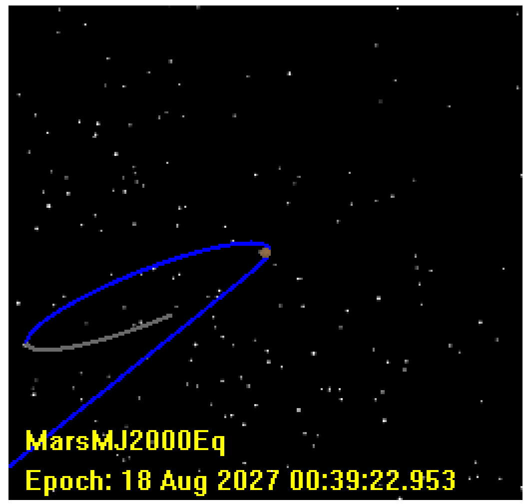

Figure 6 Initial orbit around Mars

The calculated launch and arrival times for the entire simulation campaign are listed in Table 3.

Table 3: Launch and arrival date of simulated missions

ID	launch date	arrival date
D03	02/06/2003	17/12/2003
D26	16/11/2026	22/08/2027
M26	21/09/2026	18/08/2027
L26	27/09/2026	04/09/2027
D28	10/12/2028	13/09/2029
M28	11/10/2028	24/09/2029
L28	23/10/2028	28/09/2029
D30	09/12/2030	25/09/2031
M30	11/11/2030	10/08/2031
L30	18/11/2030	07/10/2031

V. RESULTS SUMMARY: REDUCED LIFT-OFF EFFORT AND INCREASED PAYLOAD MASS?

The high-fidelity GMAT simulations allow us to obtain key data for further analysis.

A refill mission first leads to the propellant location; in our case to either the lunar orbit or the SEL2. This allows lowering the amount of loaded propellant if the depot location is sufficiently outside a gravity well and reduces the needed characteristic energy. The first effect enables to increase the payload mass accordingly.

The results for both, the permissible increased payload mass and the reduced characteristic energy are provided in Table 4 and are illustrated in Figure 7 and Figure 8. Since no propellant is needed to reach the SEL2, missions using a depot location at this location have the highest potential payload mass.

Table 4: Result summary: payload complement mass change and launch characteristic energy.

ID	payload mass/ increase wrt direct mission [kg] / [%]	launch characteristic energy, C3 [km^2/s^2]
D03	187.0 / n. a.	22.1
D26	187.0 / n. a.	25.8
D28	187.0 / n. a.	18.2
D30	187.0 / n. a.	13.5
M26	342.0 / 83%	-2.2
M28	342.0 / 83%	-2.2
M30	344.0 / 84%	-2.0
L26	424.7 / 127%	-0.4
L28	416.4 / 123%	-0.4
L30	427.0 / 128%	-0.4

Missions to the SEL2 require naturally a characteristic energy close to zero.

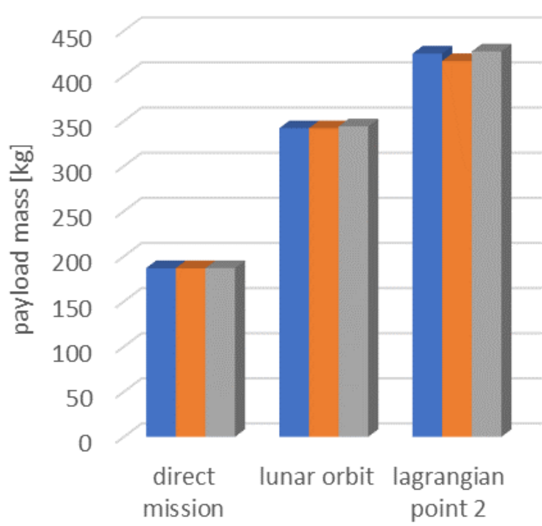

Figure 7 comparison of allowable payload mass for direct missions to Mars and for missions using space-sourced propellant stored in depots either in lunar orbit or in the Sun-Earth Lagrangian point 2.

Missions with a depot location in lunar orbit require propellant for the orbit insertion and hence can only moderately increase the payload complement. Reaching the Moon orbit is cost-efficient from a launcher point of view; the characteristic energy is significantly negative. The trajectory towards the depot location is, in fact, not an escape hyperbola but an elliptical Earth orbit.

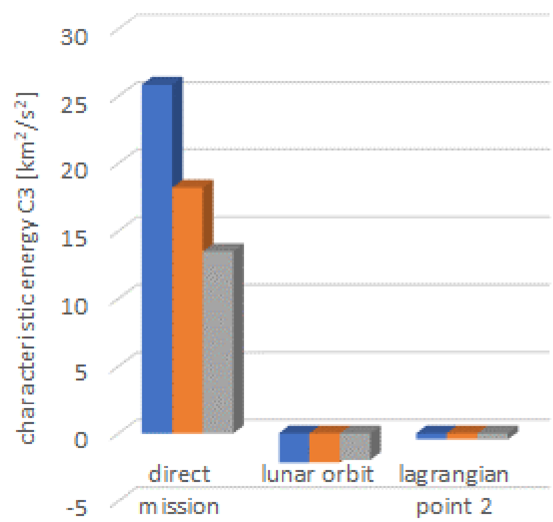

Figure 8 comparison need characteristic energy, C3, for direct missions to Mars and for missions towards the propellant depot location either in lunar orbit or in the Sun-Earth-Lagrangian point 2.

For the two refuelling mission concept, the amount of propellant to be refilled is illustrated in Figure 9.

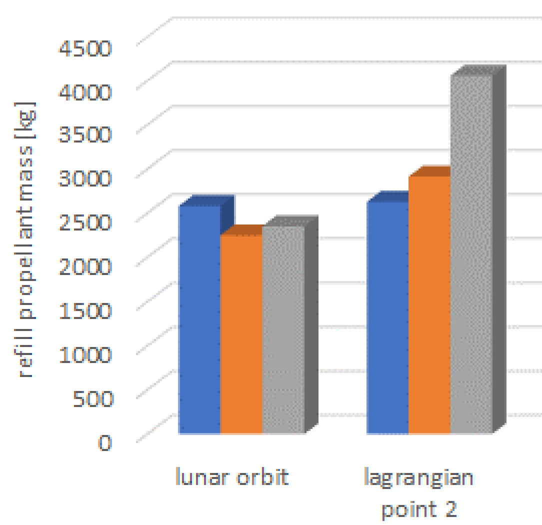

Figure 9 required refill - propellant mass for missions to Mars with propellant depots either in lunar orbit or in the Sun-Earth-Lagrangian point 2.

The amount to be refilled is of the same order of magnitude for both refill mission concepts, which is surprising at first sight since the SEL2 concept does not require an escape from a gravity well. However, the SEL2 mission lacks the Earth orMoon-flyby penalizing the propellant consumption budget.

VI. CONCLUSION: IS IT WORTH IT?

Through our research, we give a comprehensive account of how Mars Express-like missions could be conducted if propellant would be available in depots in space.

We find that significant savings in launch effort can be made while also significantly increasing the payload mass, *i.e.* the utility of the mission.

Here, the SEL2 depot wins for payload size. The lunar orbit scenario is however optimal for the reduction in launch energy. It also wins for the need of the least amount of refill propellant amount.

The improvement for missions to Mars by using depots, comes at a cost: the mission becomes more complex and the price of the refill-propellant at the depot location needs to be taken into account. We also find that large tanks for the refill-propellant are needed.

Launching empty tanks is not reasonably done due to mechanical and volume constraints or would be a massive over-design. An alternative would be the use of deployable tanks – a technology that does not exist today.

Our high-fidelity analysis also reveal that refill missions are complex and thus simple, patched conics approaches, may give unrealistic results.

The benefits of using space-sourced propellant depots are promising. Once, the main technology challenges have been resolved, it is conceivable that the use of propellant depots, or commercial gas stations, will be the new normal. This suggests a technology demonstration mission and government funded science user mission be conducted.

VII. ACKNOWLDEGEMENTS

We thank Holger Voos, Loveneesh Rana, Davide Menzio for suggestions for this research, Bob Lamboray and the Luxembourg Space Agency (LSA) for financial support and Jean-Jacques Dordain for inspiring this research.

VIII. REFERENCES

[1] D. Conte, M. Di Carlo, K. Ho, D. B. Spencer, and M. Vasile, "Earth-Mars transfers through Moon Distant Retrograde Orbits," *Acta Astronaut.*, vol. 143, pp. 372–379, 2018.

[2] NASA, "NASA Trajectory Browser." [Online]. Available: https://trajbrowser.arc.nasa.gov/traj_browser.php. [Accessed: 07-Mar-2022].

[3] "Launcher Calculator." [Online]. Available: https://launchercalculator.com/. [Accessed: 07-Mar-2022].

[4] R. Zong, M. Ludwikowski, and R. Weber, "Analysis of a Modified ESA Mars Express Mission with Use of Lunar Space Resources," in *Proceedings of the Space Resources Week 2021*, 2021.