The NASA/ESA Mars Sample Return Campaign

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***Abstract* – This paper outlines the proposed architecture of the Mars Sample Return (MSR) campaign planned in collaboration by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The goal of the campaign is to bring to Earth a scientifically selected, diverse set of Mars samples being currently collected by the NASA Perseverance rover. The planned campaign involves an Earth Return Orbiter (ERO) built and operated by ESA and a Sample Retrieval Lander (SRL) built and operated by NASA.**

The paper describes the high-level mission design and timeline of the campaign and outlines its constituent components.

I. INTRODUCTION

Returning samples from Mars has been a major long-term goal of international planetary exploration for decades. Analyses of data from past Mars missions have confirmed that some areas of Mars could have been capable of supporting life in the past, with much of this habitable period occurring about three billion years ago, when similar conditions resulted in the blooming of life on Earth. Discoveries resulting from analyzing returned Mars samples could help us understand better the origin and evolution of life on Earth [1]. The Decadal Strategy for Planetary Science and Astrobiology has stated: *"The highest scientific priority of NASA's robotic exploration efforts this decade should be completion of Mars Sample Return as soon as is practicably possible with no increase or decrease in its current scope."* The reasoning is that key scientific objectives can only be achieved via study of carefully selected martian samples in terrestrial laboratories [2].

The MSR campaign is being implemented jointly by NASA and ESA to collect and return Mars samples, and it encompasses the following elements: one mission, already at Mars, for sample collection: the Perseverance rover; one mission to deliver a Mars ascent vehicle to the martian surface and transfer to it the sample tubes; a Mars ascent vehicle to deliver the capsule containing the samples into Mars orbit; one mission for capturing the capsule from Mars orbit and returning it to the Earth; and a dedicated sample receiving facility to analyze and process the samples once they arrive on Earth.

Studies on mission architectures for Mars sample return have been conducted since at least the late 1970s [3]. Work on the formulation and design of a joint NASA/ESA campaign for the sample retrieval and return missions was kicked-off in 2008, when ESA and NASA signed an Agreement addressing potential cooperation including Mars sample return activities. The NASA/ESA partnership was reaffirmed with the signature of the 2018 Joint Statement of Intent between NASA and ESA on Mars Sample Return. The architecture of the campaign has evolved over the years, responding both to emerging technologies and capabilities, and to programmatic and budgetary constraints. An Independent Review Board (IRB) was convened by NASA in summer 2023 to assess MSR cost and schedule alignment with funding profile guidelines and to analyze architectural options that could reduce technical risks or increase schedule or cost margins [4]. The current paper describes the MSR architecture before NASA responds to the findings of the IRB.

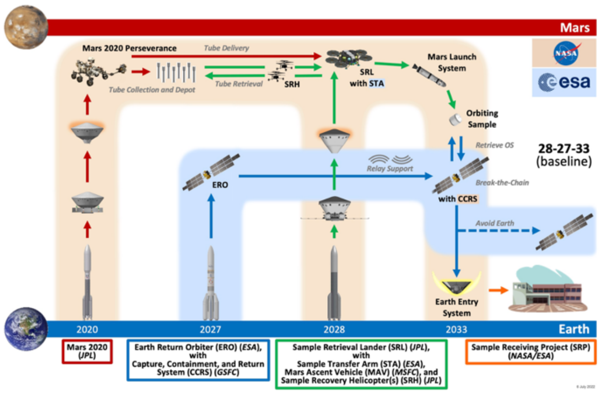

Figure 1: Mars Sample Return Architecture as of 2023

As of the end of 2023, the design of the MSR campaign had coalesced into the following elements:

1. NASA's Perseverance rover, already collecting scientifically selected samples on the surface of Mars and storing them in sample tubes.
2. NASA's Sample Retrieval Lander (SRL), including a Sample Transfer Arm (STA) provided by ESA and carrying the Mars Ascent Vehicle (MAV) to the Mars surface, where SRL will use the STA to store the tube samples into the Orbiting Sample (OS)

capsule mounted on top of MAV.

3. NASA's Mars Ascent Vehicle, carrying the OS and delivering it to low Mars orbit.
4. ESA's Earth Return Orbiter, carrying NASA's Capture, Containment, and Return System (CCRS), entrusted to find and capture the OS in Mars orbit and return it to Earth.
5. A joint Sample Receiving Facility to receive the samples and process them so they can be analyzed.

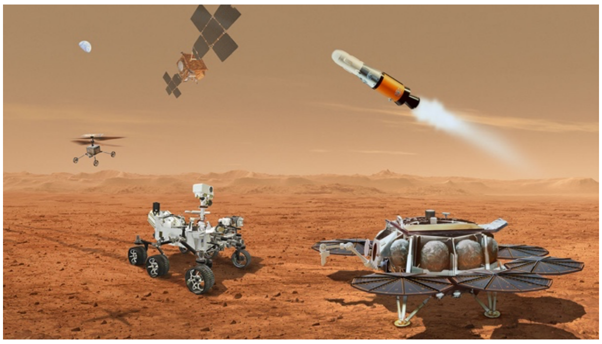

Figure 2: Mars Sample Return Concept Illustration (NASA)

This paper will focus on describing at a high-level the planned mission design for SRL, MAV, and ERO, and the overall timeline analysis, since those are the elements of more relevance for the flight dynamics community.

II. PERSEVERANCE ROVER

The Mars 2020 Perseverance rover was launched on 30 July 2020 and then landed successfully on 18 February 2021 at the Octavia E. Butler site in Jezero Crater. Perseverance carried the Ingenuity helicopter as a technology demonstration, the first aircraft to achieve powered, controlled flight on another planet.

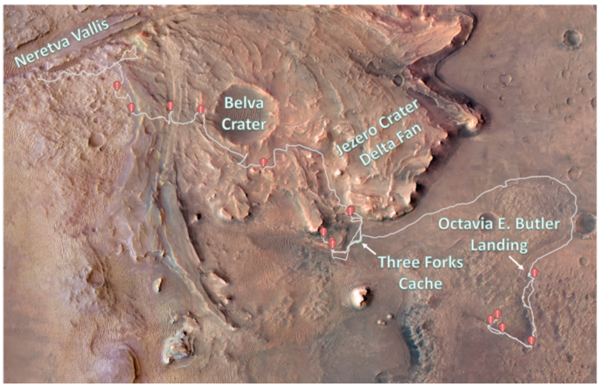

Figure 3: Perseverance Path as of March 21, 2024, Showing the Location of the Samples Taken so far (NASA)

As of March 21, 2024, Perseverance has collected 21 rock cores, 2 regolith samples, 1 atmospheric sample, and 3 witness tubes. Of those, Perseverance deposited on the Three Forks cache 10 sample tubes: 7 containing rock cores, 1 with a regolith sample, 1 with an atmospheric sample, and 1 witness tube. 12 empty sample tubes and 2 witness tubes remain to be used. The OS is designed to carry up to 30 sample tubes. The Perseverance rover will be the primary means to convey 30 of the 33 sample tubes remaining in the rover to SRL so they can be stored in the OS. The Three Forks cache serves as a backup if Perseverance cannot deliver the samples.

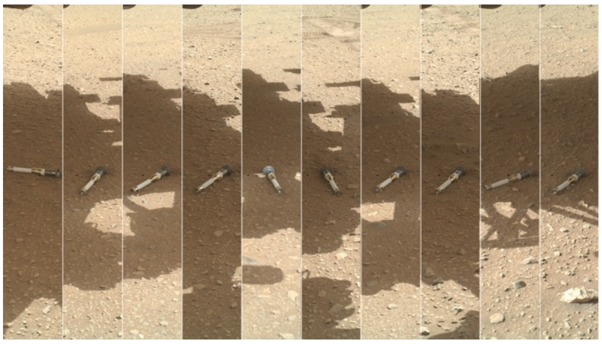

Figure 4: The Three Forks Cache (NASA)

III. SAMPLE RETRIEVAL LANDER

The Sample Retrieval Lander is designed to carry the Mars Ascent Vehicle to the Jezero Crater where the Perseverance rover would be waiting with the sample tubes. After landing it would receive the tubes carried by Perseverance and store them into the OS using the STA. When the tube transfer has been completed, SRL will prepare for the MAV launch.

SRL is planned to launch not earlier than 2028 from the Eastern Range in Florida, with a launch period of at least 20 days. For a launch between June 29 and July 18, 2028, it would arrive at the surface of Mars between October 11 and November 3, 2030, using a Type IV transfer trajectory. The launch-arrival space for SRL is constrained by the not-to-exceed spacecraft launch mass–7150 kg for the 2028 launch analysis–the expected launch vehicle performance, and the required arrival conditions. SRL is planning to use guided entry and terrain-relative navigation (TRN) to precisely land in one of several landing locations in the Jezero Crater area. The arrival needs to happen when the seasonal atmospheric cycle ensures sufficient density for descent and when the atmospheric opacity is low enough that optical TRN is feasible. These conditions constrain the solar longitude (L_s) at the EDL date to be between 30° and 97°, the lower limit due to atmospheric opacity, and the upper limit due to atmospheric density. In addition, the local time of landing must allow for proper illumination of the surface below the descent path. The images taken by the descent stage need to be matched with images taken from orbit and very long shadows could spoof the matching process, with local true solar times at landing between 10:20 and 16:20 deemed preferable. It is also required that the entry speed is not greater than 6 km/s, to be consistent with the thermal protection capability of the heat shield, and that any solar conjunctions do not take place later than 30 days before landing.

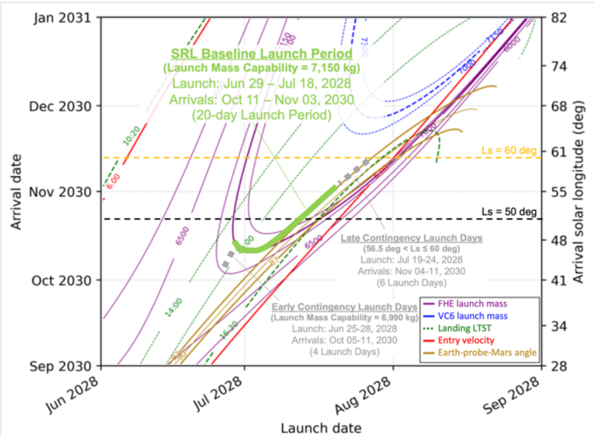

Figure 5: SRL Launch/Arrival Space

For this transfer it was also found that the angle formed by the Earth, the spacecraft, and Mars right before Mars arrival would be close to 90°, affecting the predicted spacecraft state knowledge at entry. The arrival dates for some launch days had to be postponed to change the angle by up to 3°, ensuring that the Doppler signature of the spacecraft as it was being pulled by Mars had an observable component in the line of sight to the Earth.

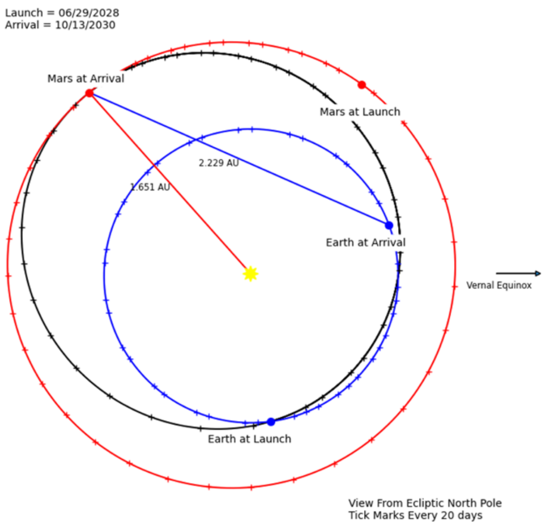

Figure 6: SRL Cruise Trajectory for the Open of the Launch Period

The arrival dates in 2030 would result in arrival L_s between 46° and 56°, an inertial entry speed between 5.517 and 5.627 km/s, and a landing local true solar time (LTST) between 14:56 and 16:00, corresponding to a Sun elevation at landing between 33° and 48°. The arrival would take place after an extended solar conjunction, with the spacecraft staying from 104 to 203 days at a Sun-Earth-probe angle of less than 3°, up to 124-170 days before the planned arrival date. The spacecraft would be at a distance between 2.08 and 2.24 AU from the Earth on arrival, farther than previous Mars landing missions.

The SRL spacecraft would be spin stabilized from launch vehicle separation to cruise stage separation and would use an X-band radio together with a low-gain and a medium-gain antenna to communicate with the DSN and ESTRACK and to generate tracking data for navigation. It would be composed of a cruise stage with solar panels and a cruise propulsion system, and a descent stage. These two stages would separate minutes before entry and the descent stage would perform guided entry to bleed most of the entry speed and reach the target landing area. Then it would release the heat shield and deploy a parachute to reduce the descent velocity. After the parachute and the back shell are ejected, it would use thrusters to perform powered descent and divert to the selected landing zone, where it would land.

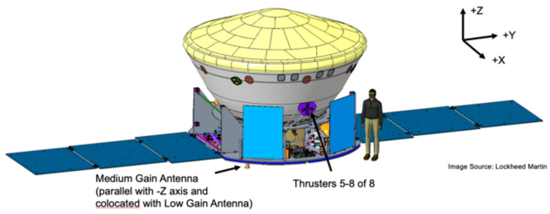

Figure 7: SRL Cruise Configuration

While on the surface, SRL would be powered by deployable solar panels. Communications with the Earth would use a multi-band radio with an X-band low-gain antenna for low-rate direct-from-Earth commanding and limited direct-to-Earth downlink capability, and a UHF antenna to communicate with the ESA and NASA Mars Relay Network orbiters, including ERO. Critical event coverage during entry, descent, and landing will use a separate UHF antenna mounted on the descent stage.

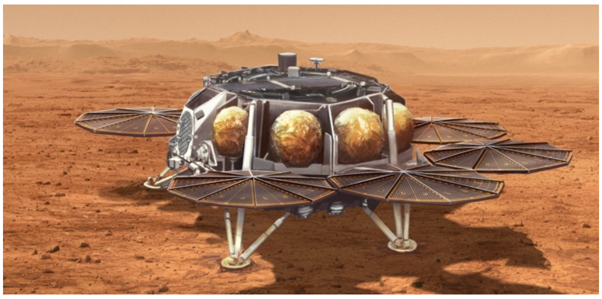
Figure 8: SRL on the Surface of Mars (NASA)

After landing and the lander commissioning, Perseverance would approach SRL and start the tube transfer process, with the STA receiving each tube and storing it in the OS. The cadence of tube transfer during the surface mission would be constrained by the energy balance for Perseverance and SRL and by the required contacts with the ground to verify that each tube is available for transfer, and that it has indeed been transferred and stored.

Should Perseverance not be capable of transferring the sample tubes to SRL, SRL would have to use other means to retrieve the tubes, either from the Three Forks depot or a new surface depot created by Perseverance. One option would be to use Sample Retrieval Helicopters derived from the Ingenuity Mars helicopter design that could pick up one tube at a time and drop it on the ground in reach of SRL's STA, with the STA picking each tube and storing it into the OS.

While the current baseline is for SRL to launch in 2028, other opportunities are available for the Earth to Mars transfer, with the 2031 Type II opportunity providing additional launch mass performance if a higher entry speed can be tolerated.

IV. MARS ASCENT VEHICLE

The Mars Ascent Vehicle would be responsible for carrying the Orbiting Sample and launching it from the surface of Mars into an orbit above 300 km in periapsis. NASA's Marshall Space Flight Center is responsible for the design of the MAV. The MAV would be carried to the surface of Mars by SRL, with the MAV stowed horizontally. The MAV, the OS and its interface assemblies form the Mars Launch System (MLS). The basketball sized OS would be designed to carry up to 30 sample tubes, protecting them from thermal and dynamical shock to preserve the integrity of the samples and keeping them contained. The OS external surfaces need to be coated to provide enough reflectivity to allow ERO to detect, image, and track it.

Figure 9: Orbiting Sample Container Concept Model (NASA)

The MAV would be composed of two solid rocket motor stages, with the first stage lifting the vehicle from the surface of Mars and into an eccentric orbit with a sub-surface periapsis and an apoapsis above 300 km in altitude, and a second stage firing close to the apoapsis achieved by the first stage and lifting the periapsis above 300 km. The first stage would be guided and would calculate the optimal time and direction of the second stage burn, releasing the unguided second stage in the optimal orientation, and then reentering into Mars. After inter-stage separation, the second stage would spin up, fire its solid rocket motor, and release the OS [5]. After this, both the spent second stage and the OS would be orbiting Mars. The MAV-OS separation impulse would be designed to ensure that the probability of recontact is small, and that the two objects separate sufficiently so ERO can safely approach the OS and capture it.

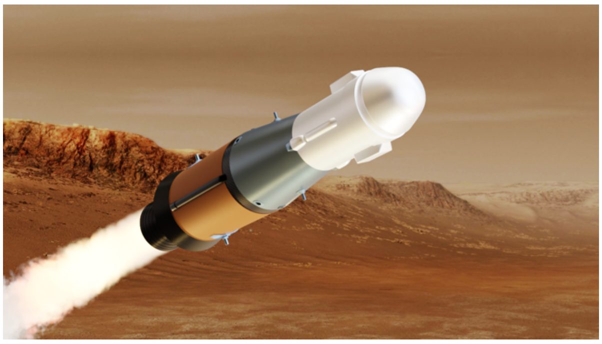

Figure 10: Mars Ascent Vehicle Illustration (NASA)

The orbit achieved by the OS would be constrained by the following bounds:

1. Its periapsis should be above 300 km to allow for ERO to safely capture it.
2. Its semimajor axis should be above 330 km to ensure that it can stay in orbit for at least 10 years.
3. Its semimajor axis should be below 500 km, to reduce the orbit dispersion and ensure reliable imaging opportunities.
4. Its inclination should be close to the latitude of the launch site and the orbital inclination of ERO to reduce the cost of inclination changes.

The MAV would be equipped with a UHF transmitter that can send telemetry from the first stage during ascent and then switch to a beacon mode, first continuous for the second stage monitoring from inter-stage separation to MAV-OS separation and transitioning later into an intermittent mode to produce Doppler beeps than can be tracked by ERO or other assets to determine the orbit of the second stage. The MAV second stage orbit will also be determined using optical images taken by ERO. The MAV second stage is larger than the OS, so it should be easier to image. Since the MAV orbit insertion uncertainty is expected to be much larger than the MAV-OS separation uncertainty, determining the orbit of the MAV should facilitate finding the OS.

V. EARTH RETURN ORBITER

ESA's Earth Return Orbiter (ERO) will carry the NASA-provided Capture, Containment, and Return System (CCRS), including the Earth Entry System (EES). An Ariane 64 launcher would launch ERO from Europe's Spaceport in Kourou, French Guiana, as early as 2027 to support an SRL mission launching in 2028. For the 2027 opportunity, ERO would launch between October 25 and November 14, 2027. The ERO spacecraft would be equipped with a solar electric propulsion (EP) system utilizing 5 RIT-2X Xenon thrusters powered by a 144 m^2 solar array. ERO would also carry an ejectable bi-propellant chemical Orbit Insertion Module (OIM).

Figure 11: ERO at Mars after ejecting the OIM (ESA)

After launch, the spacecraft would be commissioned and could start EP thrusting to achieve a Mars-intersecting trajectory as soon as one month after launch. For the 2027 opportunity, ERO would perform an Earth gravity assist about one year after launch to connect with the 2028 Earth-Mars transfer window. That would also allow for an ERO launch in 2028 with a similar Earth-to-Mars transfer trajectory.

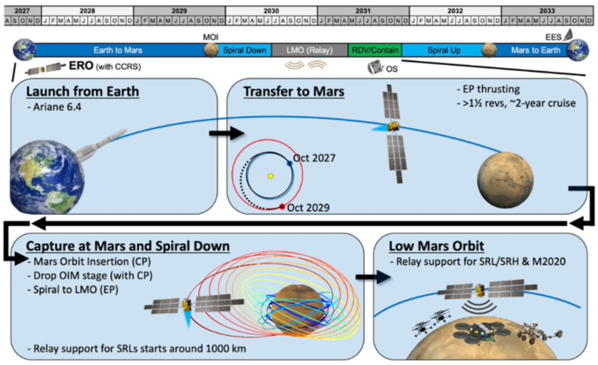

Figure 12: ERO Mission from Launch to Low Mars Orbit

After arriving to Mars on October 2029, ERO would use the OIM to capture into Mars orbit, with the OIM performing two additional burns at subsequent periapses to further lower the orbit apoapsis. After the OIM is depleted, it would be ejected into a stable Mars orbit. ERO would then use the EP system to spiral down into an orbit that can support SRL EDL relay and early surface operations, eventually transitioning to a 450 km orbit at 22.5° inclination for most of the SRL surface mission. This orbit has a one-sol ground track repeat cycle that allows for six relays passes per day over the Jezero site. The right ascension of the ascending node of the orbit precesses around Mars, with the local solar time of the relay passes changing in a 36.5-sol cycle. ERO would use one of two Electra UHF radios supplied by NASA to provide communication relay for SRL and Perseverance.

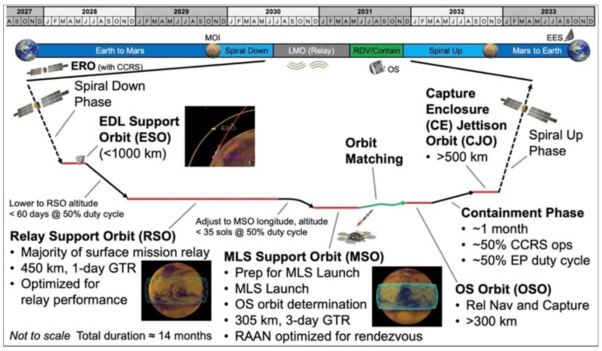

Figure 13: ERO Mission in Low Mars Orbit

ERO would transfer into a lower, 305-km orbit in preparation for the launch of the MLS. This would be a 3-sol ground track repeat orbit that will provide repeating geometric conditions for launch every three sols. ERO would provide relay support for SRL right before launch and for the MAV after launch, and then use one of its two Narrow Angle Cameras (NAC) to image the MAV and the OS. ERO would be in a lower orbit than the OS and the MAV second stage after they get into orbit, improving the optical visibility of these objects. The selection of the MLS launch windows would be driven by ERO's capture of the launch SRL and MLS UHF transmissions at the launch time and by having appropriate orbital offsets between OS and ERO after launch, so the natural drift of the ascending nodes would result in nearly matching orbital planes after a few weeks.

After the MAV is detected using both Doppler and NAC images [6], ERO would transition to an orbit 30-km below the expected OS semimajor axis to provide additional opportunities to detect the OS and better determine its orbit. Once the OS orbit has been improved, ERO would match its orbit and position itself into an orbital location with a 60 km along-track offset with respect to the OS. From this location, ERO would image the OS and precisely determine its orbit so ERO can rendezvous with it and capture it using the CCRS. During the final rendezvous ERO would use a LIDAR to track the position of the OS even more precisely all the way to capture. After the OS has been captured, the CCRS would transfer it to the EES. ERO would then start spiraling out of Mars orbit using EP again to achieve an interplanetary orbit that comes into close proximity with the Earth.

During the Earth approach, Planetary Protection requirements to avoid backwards contamination drive the ERO trajectory design. From about 120 days to 30 days before Earth closest approach, the ERO trajectory would be biased in the B-plane to ensure a naturally safe Earth flyby. EP retargeting maneuvers would gradually remove the B-plane bias, whereas chemical de-targeting disposal maneuvers would be prepared by the operations team in case the mission needs to be aborted due to loss of ERO spacecraft's integrity to safely perform the EES delivery [7].

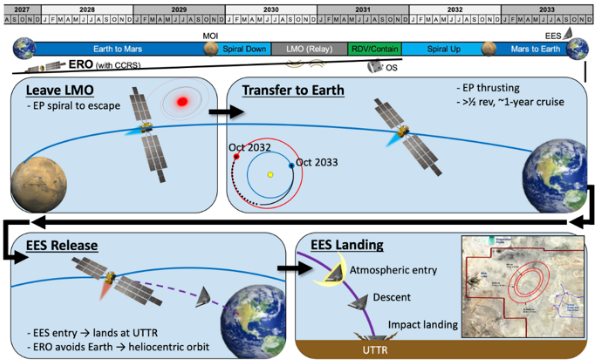

Figure 14: ERO Mission from Low Mars Orbit to Earth Return

The last 30 days of the Earth approach are known as the EES delivery phase. ERO would stay in a trajectory that safely flies by the Earth until seven days before the closest approach, when it would use its chemical propulsion system to target the Utah Test and Training Range (UTTR) landing site, release the EES, and then perform another maneuver to avoid the Earth and afterwards get into a heliocentric orbit that avoids the Earth-Moon system for at least 100 years. ERO needs to comply to strict navigation accuracy at the EES release in order to fulfill the required landing footprint 3-σ uncertainty ellipse [8].

The EES would be totally passive and would not be equipped with an attitude or trajectory control system or with a communication system. EES would be released in a specific direction, being spun up by its release mechanism so its angle of attack would be close to 0° when it enters the Earth atmosphere. The trajectory and attitude of ERO as it releases the EES would have to be controlled very precisely to ensure that EES would safely reach the designated UTTR landing zone after three days of uncontrolled free flight. The EES would not be equipped with a parachute, and it would perform a hard landing on the UTTR terrain. After landing, the EES would be transported to the Sample Receiving Facility.

VI. Integrated Timeline Analysis

A campaign as complex as the NASA/ESA Mars Sample Return requires the coordination of multiple missions with separate and, sometimes, conflicting requirements. The conditions at Mars for SRL arrival must be adequate for EDL and ERO needs to be at an appropriate altitude for EDL, surface, and MLS launch support. Figure 15 shows the nominal timeline for a campaign with ERO launching in 2027, SRL launching in 2028, and the EES returning to Earth in 2033 (28-27-33). Careful optimization of the chemical and xenon propellant loads of ERO is needed to provide enough delta-velocity (ΔV) margin to the mission to allow ERO to arrive to low Mars orbit in time and depart from it without missing the Mars-to-Earth transfer window. For a classical chemical propellant mission, the propellant tanks can be filled as much as the launch vehicle performance would allow without significantly affecting the timeline of the mission, but for an electric propulsion mission a too-heavy spacecraft may not have enough time to implement the required ΔV and therefore miss the planned orbital target [9]. With the ERO spacecraft carrying both an electric and a chemical propulsion system, the loads of each must be carefully balanced to obtain the desired ΔVs in the allocated timeline.

For the 28-27-33 baseline timeline, ERO requires roughly 10 km/s of ΔV out of its EP system, 890 m/s out of the OIM and more than 80 m/s out of its RCS system, with additional propellant carried to ensure resilience against missed thrust, propulsion system performance degradation, and unplanned contingencies. Other transfers, because of the different positions of Mars and Earth in their orbits, may require even higher nominal ΔV, requiring the spacecraft to carry even more propellant to ensure that it can return at a later transfer opportunity if needed.

The trajectories and timelines also need to be resilient to missed thrust events. While for the spiral phases missed thrust may only impose a delay, for the interplanetary transfer phases missed thrust events may require both more time and more propellant to successfully complete the transfer.

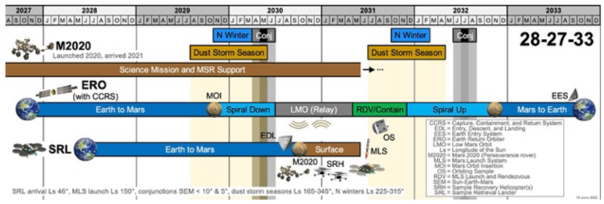

Figure 15: Nominal Timeline for the 28-27-33 Mission

The timeline for the surface mission also must be analyzed to ensure that MLS would be ready to launch in time for ERO to be able to capture it and return to Earth at the desired opportunity. The timeline from launch to capture, including MAV and OS detection and orbit determination, orbit matching, rendezvous, and capture, needs also to be carefully analyzed and each step modeled and optimized for the whole phase to fit within the allocated time span. The position of the Earth relative to Mars during the surface phase and the launch to capture phase also need to be taken into consideration, as the distance between the two planets affects the data rates that can be achieved from ERO to the Earth ground stations and some period of the mission, such as the MAV and OS imaging campaigns, would require to transmit high data volumes to the ground for processing.

Thousands of possible Earth-to-Mars trajectories and Mars-to-Earth trajectories have been evaluated to find the combination of launch conditions, Mars arrival conditions, propellant loads, and return trajectories that fulfill margin requirements for launch vehicle performance, spacecraft launch dry mass, timeline, propellant loads, and return conditions. The resulting timelines have also been evaluated to understand their sensitivity to possible changes in launch and return masses, and in propulsion system performance.

VII. CONCLUSION

The NASA/ESA Mars Sample Return Campaign would bring to Earth a set of diverse and carefully selected Mars samples. It would land the heaviest lander ever landed on Mars, it would launch the first rocket from the surface of another planet, and it would be the first mission that would do a round trip from Earth to Mars and that would return samples from another planet.

The mission analysis for such a campaign requires careful design and optimization of multiple vehicles, trajectory phases, and timelines. An ERO launch in 2027 or 2028 and an SRL launch in 2028 would allow for return of the Perseverance samples to Earth in 2033, but later launch opportunities are also possible that would result in later return of the samples.

VIII. ACKNOWLEDGEMENTS

The decision to implement Mars Sample Return will not be finalized until NASA’s completion of the National Environmental Policy Act (NEPA) process. The information presented in this paper about a potential Mars Sample Return campaign architecture is pre-decisional and is provided for planning and discussion purposes only.

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