THE SAMPLE FETCH ROVER – MISSION DESCRIPTION, OPERATIONS AND CHALLENGES

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ABSTRACT

Mars Sample Return (MSR) is an ESA and NASA-JPL campaign that aims to return to Earth a scientifically worthy set of soil samples. The campaign consists of several missions, one of which is the Sample Fetch Rover (SFR), conceived to find and retrieve back to the Mars Ascent Vehicle (MAV) a set of samples previously deposited on the Mars surface by the M2020 mission. This paper focuses on the SFR surface mission and its challenges.

1. INTRODUCTION

The Mars Sample Return Campaign [1] is the response to the long-running scientific objective to better understand Mars. Bringing Mars soil to Earth will allow scientists to use terrestrial laboratories to perform in-depth analysis of the samples. The scientific analyses on these samples are expected to enable breakthrough advances in the search for biosignatures on Mars and provide better understanding of the origin and evolution of Mars as a geological system.

The MSR architecture, outlined in Figure 1, is built on five campaign elements: four flight and one ground[1]. Each campaign element consists of one or more functional elements. The four flight elements are:

- Mars 2020 [2]: The NASA-JPL rover Perseverance is responsible for the collection of core samples and their placing into tube/glove assemblies, named RGAs - Figure 2RSTA (Returnable Sample Tube Assembly) Glove Assembly (see Figure 2). M2020 will deposit several tubes at a sample depot location to be selected during the surface mission that can be retrieved by SFR later. M2020 also represents one of the two pathways to return tubes to the SRL lander alongside SFR.
- Sample Retrieval Lander MAV (SRL-MAV): NASA-JPL mission consisting of a lander with the MAV [3] as well as an ESA provided Sample Transfer Arm (STA). The Sample Transfer System (STS), which includes the STA, is responsible for transferring the tubes from the rovers into a basketball-shaped container, named Orbiting Sample (OS), which is placed in the MAV. The MAV will then be launched into Mars orbit, where the OS will be released and captured by ERO.
- Sample Retrieval Lander SFR (SRL-SFR): Mission consisting of a lander carrying SFR. Following Entry, Descent and Landing (EDL), SRL will deploy SFR on the surface of Mars. SFR [4] is an ESA mission consisting of a rover responsible to fetch up to 30 RGAs from the depot previously created by M2020 and return them to SRL-MAV in a limited period of time defined by MSR campaign.
- Earth Return Orbiter (ERO) [4]: ESA mission consisting of an orbiter responsible for the capture of the OS, return to Earth and release the Earth Entry System (EES) to land on Earth. ERO will also provide relay services to all surface assets starting with the first SRL EDL.

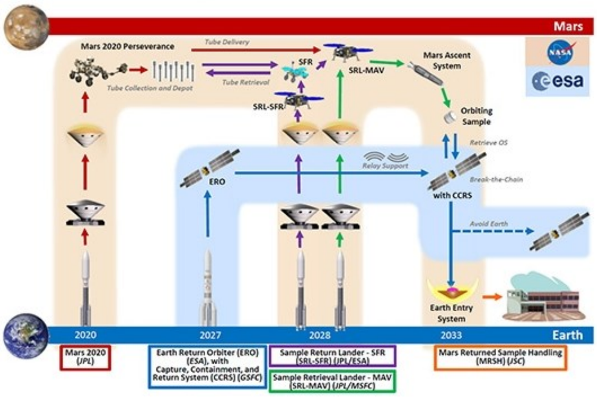

Figure 1: MSR Campaign Architecture. Courtesy of NASA/JPL and ESA

All projects are coordinated by the Mars Sample Return Program, responsible for the definition of the campaign architecture involving all missions.

Figure 2 – RSTA. Courtesy of NASA/JPL

2. THE SAMPLE FETCH ROVER

The SFR design (see Figure 3) represents an important evolution compared to the ExoMars Rover (EXM) [5]. SFR is powered by deployable solar arrays (4 panels). It

[1] The ground segment is outside the scope of this paper.

features 4 large steerable wheels (56 cm diameter) with flexible, wire mesh tyres, providing the necessary surface contact properties. The GNC system is based on two stereo cameras (NavCam for navigation purposes and LocCam for visual odometry purposes), as well as an Inertial Measurement Unit (IMU). The NavCam is mounted on a Pan and Tilt Unit (PTU) atop the SFR deployable mast. The Arm and Gripper Subsystem (AGS), designed to pick up the sample tubes, consists of a 6 degrees of freedom robotic arm, a gripper and the RSTA Detection Camera (RDC) mounted in the arm's wrist. Finally, the RSTA Storage Assembly (RSA) is placed on the rover front to store the tubes during the traverse to SRL-MAV. The on-board computing is provided by a redundant LEON2 main processor supported by a redundant LEON4 coprocessor running CPU-intensive algorithms (such as GNC, visual odometry or vision-based tube detection).

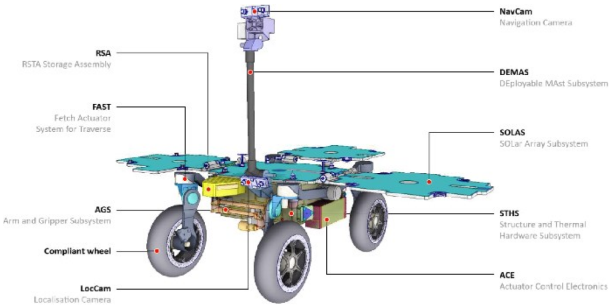

Figure 3 – Sample Fetch Rover. Courtesy of Airbus UK

3. CAMPAIGN CONSIDERATIONS FOR SFR MISSION

The MSR Campaign architecture [1] and the timeline assigned to each operational part have been defined considering the constraints and inter-dependencies of each project.

The Sample Fetch Rover will be launched onboard a Sample Return Lander in 2028, arriving to Mars in mid-2030, with the Entry, Descent and Landing (EDL) event happening not earlier than Ls0[2], which is the earliest date at which ERO can support it. SFR must complete its surface mission, exiting the designated parking area after tube transfer, as late as Ls145 in alignment with a MAV launch happening up to Ls180.

M2020 will construct two depots:

- Initial Depot: Planned for late 2022, will be placed somewhere nearby or on top of the Jezero Delta and will contain 10-13 RGAs. It is created as contingency in case M2020 will experience problems in the following years.
- Final Depot: Planned to be selected 9 months before SFR EDL, it will be constructed during the following 6 months. Further additions could be done until 2 months before SFR arrival to the depot, to give Ground Control time to plan pickup operations.

The SFR mission performance shall be ensured in a statistically worst "year" environment in terms of power generation capability / energy availability. This means that the SFR design needs to consider factors such as atmosphere attenuation, accumulation of dust deposit[3] on the solar array and extreme thermal environment fluctuations. The environmental thermal conditions drive the SFR design, as they impact the SFR survivability (energy needed at night) and the operability during each sol [4](overheating requires to pause activities).

The mission analyses have indicated mission success even when the design takes all the worst possible assumptions simultaneously on a sol basis, while keeping the rover size and mass within SRL requirements.

A considerable effort was devoted to better understand the meteorological conditions at Jezero based on local data accumulated by previous orbital missions. Figure 4 gives an appreciation of power availability range which shall be considered due to meteorological conditions (sol to sol, and in a cumulated way through progressive dust deposit accumulation on SA panels), some interesting system variables such as SFR tilt / local slopes, and arrival date. Storms in Jezero during the mission period (local spring and summer) are only local and were found statistically short, but intense and very quick to rise (hours). The dust deposition model was also refined (sizing) and is Ls dependent.

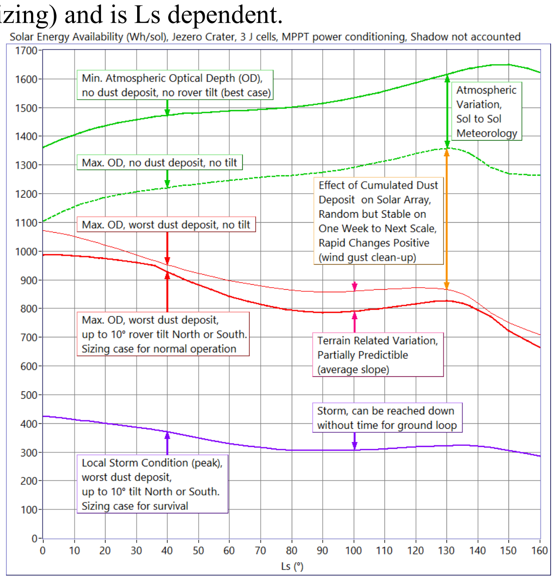

Figure 4 - Estimated Energy/Sol for main scenarios

4. THE SFR SURFACE MISSION

SFR differs from previous Mars rover missions which

[2] Solar longitude.

[3] Drives performance after 90 sols of surface mission.

[4] Mars day.

focused mainly on science return from in situ analyses. Unlike those, SFR is designed to traverse efficiently long distances per sol and pick up several tubes per sol autonomously in a limited time bounded by the SRL-SFR EDL and the MAV launch date. The time constraint has important consequences in terms of SFR performance requirements and is the source of several technical challenges, particularly for what concerns fast mobility, autonomous navigation and sample tube detection and pickup capabilities (see Section 5). The mission is limited to a maximum of 345 sols distributed across different phases, illustrated in Figure 5.

Figure 5 - SFR Surface Mission Phases and Bounding Durations

Mission analysis campaigns are conducted periodically to assess the compliancy to timeline requirements and take corrective measures if necessary. Mathematical models of SFR required functionalities (in the power, thermal, navigation and operations design areas), the applicable environment (temperatures, optical depth), terrain (paths, Cumulative Fractional Area (CFA) [13], slopes, forbidden areas) and pass allocation are used as inputs to simulation tools to evaluate the time required for each phase.

The timeline duration for each phase is calculated according to Equation 1:

$$Duration = Base \times (1 + Operations\ Penalty) \times (1 + Lost\ Sols) \times (1 + Timeline\ Maturity\ Margin) \times (1 + Campaign\ Timeline\ Margin)$$

Equation 1 - Phase Duration

where:

- Base: Current best engineering estimate.
- Operations Penalty (OP): Penalty paid due to inability to command the rover due to relay coverage or ground segment staffing. This value is based on analysis and will be refined along the project development.
- Lost Sols (LS): Expected operational issues affecting the system availability. Lost Sols can be caused by anomalies at SFR level, related to (interaction with) the Martian environment, rover system matters, issues in the relay network impacting the forward/return communication link to/from the rover, or Ground System issues. Lost Sols can be derived from the Mean Time To Recovery (MTTR) from the anomalous conditions by means of statistical analysis.
- Timeline Maturity Margin (TMM): Accounts for uncertainty of the flight system capability and performance. This margin decreases progressively throughout the development according to ECSS standard down to 5% by Qualification Review.
- Campaign Timeline Margin (CTM): Campaign-level margin that accounts for uncertainty in operations performance, major operational issues and "unknown-unknowns". CTM is 100% for the entire mission based on NASA-JPL experience.

The region over which the MSR surface mission will take place is illustrated in Figure 6. Jezero (JEZ) was selected as the landing site for the M2020 prime mission. This site was selected with the goal of traversing out of Jezero Crater and towards the Midway (MDW) landing site candidate in its extended mission. Together, this region is referred to as the Jezeway (JZW) Region.

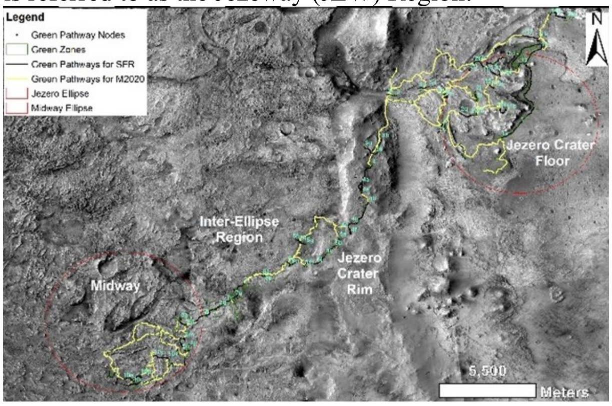

Figure 6 – HiRISE images of the Green Zones and Pathways in the JZW Region. Courtesy of NASA/JPL and ESA

Benign terrain areas called Green Zones, suitable for SRL landing or sample tube depot construction were identified along the JZW region based on HiRISE images [6]. Green Zones are defined as flat, smooth regions with low rock coverage and are connected by Green Pathways, which are paths less than 2km in length with terrain features considered to be both (1) traversable by an SFR with wheels approximately 55cm in diameter; and (2) sufficiently frequent in occurrence to ensure an even distribution of Green Pathways across the JZW region. Most Green Pathways are largely dominated by smooth regolith, considered to be the least demanding driving terrain. Additionally, most of the Green Pathways exhibit low (<5%) CFA covered by rocks, but short patches of CFA 10% can be found across JZW as well. The maximum of 20° slope permitted varies by Terrain Class and CFA. This maximum slope value corresponds to some areas identified on top of the Jezero Crater rim, an area of strategic and scientific importance where M2020 may decide to create a sample depot.

In the following sections the operations and the associated timeline assigned to each surface mission phase are described.

4.1. Critical Post-Landing Activities (CPLA) and Egress

This phase starts after completion of the EDL sequence. The lander performs essential activities for the survival of the spacecraft and preparation for SFR egress. SFR itself will be powered on and send initial health status telemetry (TM). During this phase, SFR receives power and data from the lander via a dedicated umbilical. The base estimate to complete CPLA activities is 1 sol.

Egress starts after CPLA completion. During this phase, SFR shall prepare all essential equipment for operations before umbilical disconnection, including deployment and commissioning of the locomotion system, mast and solar arrays as well as checkout and commissioning of Navcam, LocCam and the communications system. Egress is completed once ground segment has verified that the umbilical has been successfully disconnected and retracted. A concept of egress is illustrated in Figure 7:

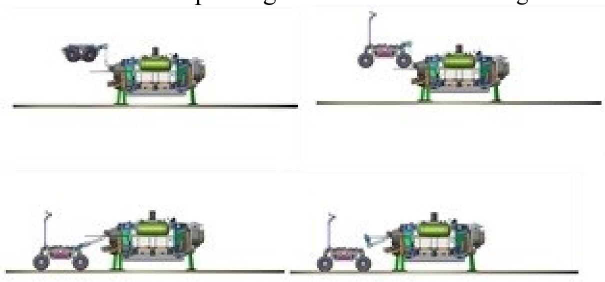

Figure 7 - Key Egress SRL/SFR configuration. Courtesy of NASA/JPL and Airbus UK

The estimated total duration is 9 sols including 5 sols base duration, 18% OP, 25% LS and 20% TMM.

4.2. Surface Commissioning

This phase commences immediately after SFR egress and involves the deployment of the rear solar panel and the commissioning of the navigation system, in particular the autonomous navigation modes. Surface Commissioning has been defined as a standalone phase, to separate its complexity and related operational/timeline uncertainties from the actual traverse phase to properly frame the traverse feasibility analysis.

The commissioning of certain navigation modes requires specific terrain conditions. Therefore, the completion of this phase might be delayed until the rover encounters appropriate conditions during the next phase.

The estimated total duration is 18 sols including 4 sols base duration, 50% OP, 25% LS, 20% TMM and 100% CTM.

4.3. Traverse To Depot and Traverse to SRL

Traverse represents one of the core activities of the surface mission. It is split in two sub-phases:

- Traverse to Depot: Starts once the surface commissioning is completed and finishes once the rover arrives to the depot entry zone, a designated area where the dedicated navigation mode is commissioned.
- Traverse to SRL-MAV: Starts once SFR has picked up and stored all designated tubes from the depot and is completed once the rover arrives at the vicinity of the lander.

The current baseline is that SFR shall be capable of traversing map distances[5] of up to 2km in a maximum duration of 92 sols (including margins), covering distances over 300m/sol. There are two key design drivers to achieve this objective: energy efficiency and autonomy (notice that rover speed is not crucial, as even a rover moving at 2cm/s could cover distances of 300m in 4.1 hours of traverse):

- As SFR is solar powered, it needs to optimize the use of the daily available energy to be able to traverse such long distances. This is achieved by a combination of rover operational modes in which any equipment not required is turned off, as well as by an effective thermal design.
- SFR shall maximise the use of autonomous driving so that it can make use of the available energy to cover long distances without ground intervention (ground commanded direct drives are bounded to approximately 50m as the uncertainty to determine a safe path beyond this point based on on-board images is too large).

Operations

SFR shall have on-board an activity plan pre-loaded, including all the parameters pertinent to the path to be traversed, waypoints, navigation mode for each segment and the communication passes for several sols, in order not to run out of activities. SFR can perform multi-sol operations, meaning that it doesn't need a ground in the loop (GITL) tactical cycle[6] every sol to continue operations[7].

Current simulations have shown that operations shall start at 10:00 and be completed at 16:00 Mars time (for every phase) based on different parameters such as available sols, estimated energy available/required per sol, environmental conditions such as Optical Depth (OD) or temperatures. This estimation will be updated during the development phase and during the surface mission by ground with in-situ information from SFR.

[5] Estimated distance of a path before it is executed. In opposition, odometry distance represents the total distance including slippage, unplanned deviations, etc.

[6] A tactical cycle consists of a Return pass (to Earth) with decisional data followed by a Forward pass (to Mars) with the activity plan required to continue operations.

[7] A nominal GITL cycle is estimated to require 10 hours including 4 hours latency from/to Mars plus 6 hours of ground planning.

At the beginning of the sol, SFR wakes up and initiates the warm-up to get all components within operational temperatures (that applies to every sol in any phase). It then starts navigation in the corresponding mode, which will be typically autonomous (see Section 5.3) in case the terrain is benign. Certain terrain configurations will exceed nonetheless the autonomous drive capabilities, in particular bottlenecks, scarps, difficult local geometries, and complex mixtures of hazardous terrain. In these cases, ground segment will have to manually command "direct drives", an approach that is called Human-Directed Drive or HDD, for which multi-sol operations won't be possible.

As in any other phase, traverse will only be interrupted in case SFR has allocated a communication pass or transitioned to sleep, which might be required for different reasons such as battery recharge or at night.

Mission Analysis

As indicated in Section 3, several paths have been identified to connect potential landing sites and depot areas. These paths have been created taking into consideration M2020 and SFR navigation capabilities and have been used to define hundreds of traverse cases, combining paths, landing dates and surface mission starting dates. The traverse cases are used to define campaign and mission level requirements, traverse operations concepts and to evaluate SFR mission feasibility based on statistical analysis.

All paths have been analysed and areas requiring HDD have been identified: the fraction of the terrain requiring HDD impacts the Operations Penalty and consequently the total traverse time. The table below illustrates one of the traverse cases estimated as time-bounding in simulations.

The estimated total duration of one of the time-bounding traverse cases is 74 sols including 36 sols base duration, 37% OP, 25% LS, 20% TMM and 100% CTM.

4.4. Tube Pickup

The other core activity of the surface mission is tube pickup. The phase starts once SFR has arrived at the RAS commissioning zone and is completed once all the designated tubes have been picked up.

Unlike autonomous navigation, which has already been successfully demonstrated in previous and current Mars missions (although with less demanding requirements), detecting, grasping and stowing of sample tubes autonomously from the surface of Mars is a first.

The current baseline is that SFR shall be able to collect up to 30 tubes in a maximum of 91 sols (including margins). Considering that the current estimated duration to collect a tube using Human-Directed Pickup (HDP) is ~3 sols (without margins), the key design driver in this phase is the capability to pick up several tubes per sol autonomously in a robust manner. This presents several challenges introduced in Section 5.4.

Operations

At the beginning of the sol, SFR shall have an activity plan available with an ordered list of tubes to pick up, the paths leading from one tube to the next and whether the tube is to be picked up autonomously or not (ground segment will be able to determine this in advance based on M2020 imagery[8]). SFR will initiate a traverse (if necessary) based on ground pre-planned paths towards the next tube, performing Absolute Global Localisation or AGL-D (see Section 5.3) periodically to eliminate localisation drift. Several paths must be defined between two tubes to cover different scenarios: a direct path to the next tube in case the current one was picked up successfully, or an indirect path with an initial backwards drive otherwise. A final approach from ~3m will allow to park the rover in the desired attitude wrt the tube. Two different final points will be defined to avoid tube detection operations with the sun in the field of view. SFR will select on-board the optimal path to the next tube.

Once parked, pickup operations will be conducted by the SFR fetching system while the rover remains stationary. The first step is the visual detection of a tube, which might be partially covered by a thin layer of dust. This process will also provide the tube position from which a grasping point is derived. SFR will calculate on-board a collision-free arm motion plan to pick up the tube. Before the final arm approach and grasp, the tube pose is refined using an additional image from the RGA Detection Camera (RDC) mounted on the arm-wrist. Once the tube is grasped, it is placed in the field of view of the NavCam and a grasp check is executed. If the grasp check is positive, the AGS moves the tube to a re-grip bracket, extracts it holding the glove end and stores it in a pre-designated slot of the RSA.

SFR will retry the detection or gasping in case of failure: in the case of detection, certain camera parameters will be altered to increase the probability of success. If SFR doesn't manage to pick up a tube after exhausting all possible retries, it will proceed to the next tube so that no time is lost, and the tube will be marked for HDP. Another scenario for HDP is in case ground segment decides so in advance, based on the images of the depot provided by M2020. In either case, SFR will park next to the tube, take images, and send them to ground segment, which will be responsible to provide the rover with a plan

[8] M2020 depot images will be provided at least 6 months (but potentially several years) in advance of SFR EDL.

to pick up the tube. This process might take several sols during which ground segment receives new data from SFR and update the plan.

Mission Analysis

Several tube/terrain geometric cases and 3D meshes coming from Curiosity imagery (with tubes added to the terrain) have been used to specify requirements, define the operations concept and perform mission feasibility analysis.

As for traverse, certain tube/terrain configurations will exceed the on-board autonomous capabilities and will require HDP, in particular when tubes are inside cracks or wedges (basically a "V-shaped" crack) or besides rocks. Probabilities for detection and grasping success have been calculated for the different samples in the terrain meshes and used in thousands of simulations to calculate the tube pickup timeline using the 3-sigma value.

Given the statistical nature of tube pickup and the different margins to be applied for autonomous and HDP operations, it is difficult to present a single timeline scenario. The following assumptions have been used to derive the campaign pickup timeline requirements based on early simulations:

- 4 sols required to commission AGL-D and RAS including picking up the first tube.
- 10% of the tubes require HDP.
- On average, picking up a tube with HDP requires 2.5 sols.
- HDP margins: 5% OP; 25% LS.
- Autonomous Pickup margins: 25% OP; 50% LS; 20% TMM; 100% CTM.

The estimated total duration (based on the assumptions above) is:

  - HDP (4 tubes): total 36 sols, including 12 sols duration calculated as the sum of 4 sols (commissioning) + 3 tubes * 2.5 sols, 5% OP, 25% LS, 20% TMM and 100% CTM.
  - Autonomous (26 tubes): total 54 sols, including 12 sols base duration, 25% OP, 50% LS, 20% TMM and 100% CTM.

4.5. Tube Transfer

The tube transfer phase starts once SFR has completed its long traverse, approximately 20m away from the SFR-MAV lander. It is divided into three sub-phases:

- Parking: Final traverse, commanded by ground to place the rover in the final parking position. It is estimated to require 3 sols.
- Tube Transfer: Tubes are moved from SFR to the OS by the STS. The current minimum estimated duration is 10 sols.
- Exit: SFR will exit the Tube Transfer Zone (TTZ) upon commanding from ground. The manoeuvre will require 1 sol.

Operations

Both Parking and Exit manoeuvres are commanded as "direct drives" with the paths pre-planned by ground. The start and completion also need to be confirmed by ground. During the actual transfer of tubes, SFR shall remain idle except for a communication pass every three sols for health check reasons[9].

5. MISSION CHALLENGES

5.1. Timeline

Unlike previous rover missions, the success criteria for SFR is binary: it must return in time the designated number of tubes or otherwise the MAV might miss the launch window. The SFR timeline is driven by three main factors: 1) Operational time: the time required to conduct the surface operations by the rover; 2) Energy: the available energy to execute the planned operations (see Section 5.2); and 3) Decisions (Ground Control interaction): the dependency on ground control to take decisions and pass them to the rover in due time.

These three factors, coined as TED, must be balanced in the rover and mission design: the rover must be able to achieve the mission within the time and energy constraints. At the same time, the MSR Program must identify bounding mission scenarios in line with SFR capabilities. To solve this circular problem, mission feasibility and survivability analyses have been conducted since the early phases of the Campaign definition to allow for a continuous refinement of rover and mission requirements. These analyses represent a complex trade-off exercise in which the inherent uncertainty associated to the development stage of the different campaign elements and the associated risks must be analysed and compensated with sufficient margins. Key program-level requirements such as the start/end of SFR mission, bounding traverses or maximum time to pick tubes could be defined thanks to this approach. The following sections go into details of challenges in specific areas such as power or navigation that impact the overall mission timeline.

5.2. Power and Thermal

SFR rover relies purely on solar energy (no Radiative Heater Unit), and solar energy availability is key driver. The rover design is focussed on its ability to use all the available energy by modulating autonomously and on a

[9] As the transfer sub-phase is not the responsibility of SFR, no further details on timeline duration are provided.

large scale, the sol-to-sol activity, that is: being able auto-adapt to meteorological conditions as actually encountered in real time.

The operation is driven in kind of bang-bang modulation, keeping the battery state of charge between 2 thresholds:

- One below which, the rover ends / interrupts its operations and redirects all the energy resource to recharge the battery: with only 8W + thermal control as power budget in this sleep mode.
- One above which, the rover wakes-up and resumes all the action it can (typically starting to discharge the battery by doing so).

The main SFR duty is traverse, so the objective is to drive as many drive/recharge-battery sequences as possible. The power system is sized to sustain a dense enough operation plan to ensure overall mission completion in time. Survival to storms is not the sizing need. In classic term of power and energy, the balance is considered on the mission sub-scenario scale, i.e., possibly weeks.

The battery is in principle quite large as it holds both enough power to supply operation peak power, and enough energy below the sleep threshold, to support next night and even further, in case of storm. In practice however, the battery remains limited: about 1kWh nameplate, i.e., identical to EXM, and more fundamentally, the solar array size is strict minimum, which stands primarily in volume by direct and ripple effect, but also in mass consecutively: cell surface is about 2/3 of EXM ones.

5.3. Autonomous Navigation and Locomotion

As mentioned in the sections above, the tight timeline requirements and mission objectives in terms of traverse translate into significant distances to be covered by the rover each sol, in the order of hundreds of meters, which render necessary the implementation of autonomous navigation capabilities onboard the SFR rover. While such functionality has been already implemented for the ExoMars rover [8], SFR requires this to be redesigned to increase the traverse efficiency, so that the navigation stop time can be minimised and the traverse distance per sol extended to meet the mission requirements. This is achieved by a faster roving platform on one side (6.67cm/s of nominal traverse speed) and a faster computing processor and co-processor modules on the other side [9], which have allowed the implementation of a new (more efficient) navigation mode called FOPSA (FOllow Path with Safety Analysis) [10]. In addition, in order to deal with the longer daily traverses of SFR, two new functionalities have been developed. These are meant to reduce the drift in localisation that inevitably builds when the rover performs its relative localisation estimations based on visual and inertial odometry data. These new functions are the Sun Sensing (SS) and the Absolute Global Localisation (AGL). The first one is meant to correct the heading estimation using the Sun as a “guiding star”. The second is meant to correct drift in the position of the rover on the global reference frame of Mars. AGL is to be used in two different modes corresponding to different mission phases. During the traverse to the sample depot, AGL-T shall use the HiRISE maps as reference in order to co-register them with local maps taken by SFR navigation cameras. During depot operations (AGL-D), maps generated by M2020 images shall be used as reference. AGL guarantees that the localisation drift is bound, instead of growing “indefinitely” along the traverse. This is crucial for the rover to follow with sufficient accuracy the global path to reach the depot during the traverse phase and later on be capable of placing the rover at a distance from the RGAs within reach of the arm system during the depot phase, reducing the need for GITL validations or corrections that would jeopardise the mission timeline.

AGL is a challenging function that has never been implemented before on-board a rover mission. The robustness of this technique will depend on the reference maps coming from HiRISE and M2020, in particular on their reliability in terms of sufficient amount and uniqueness of features or signatures and their invariance with respect to environmental conditions, so SFR can use them as tracking points to co-register against.

Sun Sensing techniques have been used in previous rover missions. The challenge to implement them robustly mainly depends on the sensor accuracy and noise levels of the IMU accelerometers, PTU encoders and the estimation of sun centroid within the camera images.

5.4. Autonomous Tube Pickup

SFR shall be able to pick up tubes autonomously with high confidence (see illustration on Figure 8). This must be achieved in non-deterministic conditions including a variety of terrains, illumination conditions and possible dust accumulation on the top and on the side of the tubes. These challenges, further detailed below, are being faced with the development of new cutting-edge technologies.

An important factor to be considered is that a depot (particularly the initial depot) will be created as early as 2023, seven years before SFR collection in 2030. The environmental conditions (e.g., dust accumulation, variety of terrains, etc) make uncertain how the tubes will look like once SFR arrives to the depot. The Visual Based Detection Software (VBDS) on-board SFR is responsible for the tube localisation and detection. It is based on machine learning algorithms [11] [12], which make it robust to such uncertainties. Synthetic and real images sets have (and will be) developed to properly train the algorithms. VBDS is also responsible to assess that the tube is properly grasped before initiating the storage sequence.

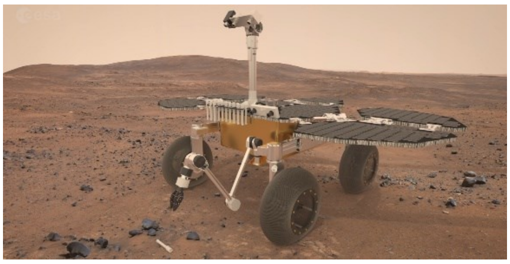

Figure 8 - Recreation of SFR picking up a tube

Autonomous pickup operations will be conducted in an unstructured scenario where local slopes or obstacles, such as large rocks and small pebbles, might impede the arm approach and grasp. To solve this issue, the AGS hardware shall be designed such that the repeatability of its operations is guaranteed within well-defined accuracy bounds. Moreover, it requires the implementation on-board of an arm-motion planner with collision-avoidance and deflection compensation, allowing to plan and re-plan the arm trajectories safely.

These autonomous operations must be performed in a range of illumination conditions caused by multiple factors such as the sun elevation, the optical depth (how much dust is there in the atmosphere) or the shadows casted by the rover and surrounding geography. Once again, the robustness of the software to handle these variations and uncertainties is crucial.

Finally, vision-based algorithms such as those mentioned above are typically computationally intensive, which is an important challenge given the limited memory and computing capability of even the most advanced flight computers.

5.5. Communications

The MSR Campaign has been conservatively designed to use ERO as the only orbiter providing communications to all the MSR surface assets[10]. With this in mind there are certain challenges that have been considered and recognised.

First, as highlighted earlier in this paper, there are numerous MSR assets which are part of this campaign of activities. All the assets will require some level of communications support from ERO. This scheduling also means that at certain times another asset may be assigned priority for communications over another. Also, under nominal planning constraints each asset expects a morning pass for forward link purposes and an evening pass for data return purposes. This then allows operations a window to post process the received data in advance of the next forward link session.

Early in the development of ERO, the decision was taken to update the Electra transceiver with the capability to provide simultaneously dual channel communications. This helps to better manage the overlapping relay needs with the numerous assets.

The orbiter starts providing communications services while still spiralling down to the Relay Support Orbit (RSO). During the spiral down, the relay capabilities are constrained by the need to perform a 50/50 duty cycle with the electric propulsion system. Once RSO is reached, ERO will be able to provide six overflights of the Jezero crater in a regular repetitive pattern.

The SFR rover is required to be capable to exchange via the orbiter a maximum of 300Mb of data in each single pass. The sizing of the data volume per pass is a key parameter because of the latency to return the data to Earth and the time needed on Earth for processing in advance of the next Forward link session for command uploads to the SFR. Should the relay pass allocated either be insufficient in capacity or occur at sub-optimal times, this can require additional or later relay slots to be pre-planned. Also, a consequence of this constraint is that the return of the critical data takes an additional sol. This delay effectively impacts the overall operational efficiency and the timeline for SFR to complete its Martian activities before the seasonal dust storms arrive.

6. CONCLUSIONS

Returning samples from Mars requires the development of a new class of spacecrafts and surface assets.
In the case of SFR, the rover design must ensure high levels of autonomy, with capability to operate for several sols without ground intervention. This requires the development and qualification of a number of key on-board technologies including self-global localisation, autonomous long-distance navigation on Mars, autonomous object detection and manipulation with the robotic arm and autonomous activity plan management with limited on-board resources (power, thermal control, data computation and communication).

The bounded time to achieve the mission objectives require the development of a require the development and qualification of a rover with high performance and reliability. Extensive analyses and simulations campaigns are run since the early phases of the development to demonstrate mission feasibility.

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[10] Of course, the intention is to use the Mars Relay Network in case the spacecraft are still alive.

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