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First Definition of Lunar Operations Taking Into Account Human Factors

Gregory Navarro[a]*, **Clara Laforet**[b]*, **Gerard Galet**[c], **Alexis Paillet**[d]

[a] *Spaceship France Project, Subdirectorate Exploration and Human Space Flight, CNES (Centre National d'Etudes Spatiales), 18 avenue Edouard Belin 31400 Toulouse, France,* gregory.navarro@cnes.fr
[b] *Spaceship France Project, Subdirectorate Exploration and Human Space Flight, CNES (Centre National d'Etudes Spatiales), 18 avenue Edouard Belin 31400 Toulouse, France,* clara.laforet@cnes.fr
[c] *Subdirectorate Space Operations, CNES (Centre National d'Etudes Spatiales), 18 avenue Edouard Belin 31400 Toulouse, France,* gerard.galet@cnes.fr
[d] *Spaceship France Project Manager, Subdirectorate Exploration and Human Space Flight, CNES (Centre National d'Etudes Spatiales), 18 avenue Edouard Belin 31400 Toulouse, France,* alexis.paillet@cnes.fr
* Corresponding Authors

Abstract

The lunar ambitions of NASA's Artemis program spell out multiple crewed missions to the Moon and later to Mars. The ESA Terrae Novae 2030+ exploration strategy roadmap aims to enable Europe's participation in the first crewed exploration mission to Mars. Yet, missions to deep space still pose significant challenges in terms of crew autonomy. As missions will become longer and more distant, the operations and sustainability of such structures in stressful isolation conditions constitute a high level technological and human challenge. For the Moon, the aim is to set up a permanent, sustainable base in several stages, including the installation of an energy production plant, the use of local resources to produce water and oxygen, the deployment of autonomous rovers and the creation of temporary habitats. The objective of Spaceship FR team at CNES (Centre National d'Etudes Spatiales - FRANCE) is to develop innovative technological bricks for the future Moon and Mars bases, thanks to technologies and skills of its network of partners: academia, laboratories and industries. To this end, the Spaceship France project team is developing a range of equipment to ensure that future crews are as autonomous as possible. These include an autonomous habitat, an assistant rover, a supervision and support system based on artificial intelligence, a physical and mental health maintenance cell and a food production system. Because of the distance involved, communication times no longer allow real-time support from earth-based control centers, as is currently the case with the International Space Station. This implies profound changes to the operational concept, and the need to take human factors into account in the definition of missions and operations. To prepare, plan and design the future lunar operations, Spaceship France project with the CNES operation teams decided to use the results of the latest human factors studies to critically analyze past lunar operations, in particular surface operations, and current CNES satellite operations. This paper aims to present how taking into account human factor will contribute to the optimization of CNES satellite operations, to the definition of the future operational concept for manned lunar and Martian surface activities and initiate best practices in human factors considerations in the definition, deployment and implementation of operations in future control centers for lunar operations.

Keywords: Spaceship FR, operation, human factor, Moon.

Acronyms/Abbreviations

CNES	Centre National d'Etudes Spatiales
DRMs	Design Reference Mission
EB	Ejecta Blanket
EHP	Extravehicular Activity and Human Surface Mobility Program
ESA	European Space Agency
ExPeRT	Exploration Preparation, Research and Technology
EVA	Extra-Vehicular Activity
HAMSTERS	Human – centered Assessment and Modelling to Support Task Engineering for Resilient Systems
HLS	Human Landing System
HSIA	Human-Systems Integration Architecture
HTA	Hierarchical Task Analysis

ISS	International Space Station
IV	Intra-Vehicular
LEO	Low Earth Orbit
MCC	Mission Control Center
NASA	National Aeronautics and Space Administration
PersEIDS	Personalized EVA Informatics and Decision Support
PSR	Permanent Shadowed Region
ROI	Region Of Interest

1 Introduction and Context

The goal of NASA's Artemis program [1] is to send multiple crewed missions to the Moon beginning in 2028, to build a permanent base. After testing the various technologies necessary to live on the surface of the Moon, the objective is to transfer them to Mars. France signed the Artemis Accords on June 7, 2022 [2]. France is also member of ESA and participates in the Terra Novae 2030+ program [3]. In this program, the ExPeRT (Exploration Preparation, Research and Technology) team integrates, coordinates, and manages the development of studies and technologies for future Exploration missions to low Earth orbit, Moon and Mars destinations. In the ExPeRT program, the Spaceship projects teams network work on innovative technological components for future Moon and Mars bases [4]. As part of this network, CNES created the Spaceship France project [5]. The French team works on seven technical areas: Habitat, Robotics, Life Support Systems, Human Health & Performance, Energy, In-Situ Resource Utilization, and Digital Technologies [5]. The objective is to provide a portion of the landed assets as well as innovative systems to CNES space partners starting in 2025 anticipating the return of humans to the Moon. CNES aligns with NASA’s strategy to offer technologies and landed systems for Moon missions, allowing thorough testing before their eventual transfer to Mars.

One of the main constraints is the communication delay between Earth and Mars. Currently, for ISS operations, delay between control center and the station is less than a second. Operational support from ground control can be done in near-real time. Between Earth and the Moon, the delay can be as much as ten seconds; it was three seconds for Apollo missions. Operational support from ground control is no more done in real time. Furthermore, given the configuration of the planets, communication between Earth and Mars takes between 3,5 and 22 minutes [6-7]. To help teams design missions and execute operational activities, adapted operational concept must be designed for human spaceflight operations on Moon and Mars taking into account the fact that it is not possible to obtain real-time support from the control center. Best practices from control center managing operations for satellites or rovers can inspire the future concept of operations.

Currently, NASA’s Moon to Mars Architecture Document defines the elements needed for long-term, human-led scientific discovery in deep space [7]. Concept of operations is declined from the envisaged use cases (cf. Fig. 1). To achieve this, NASA begins with its broadest goals—those farthest in the future on the timeline—distills them into the necessary capabilities, and then maps them to the specific elements, systems, and hardware that will take us back to the Moon and beyond.

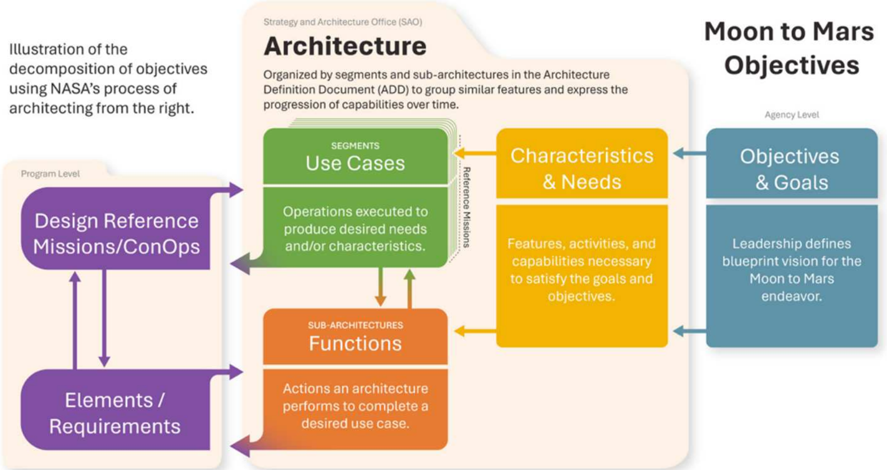


Fig. 1. NASA’s Moon to Mars architecture definition strategy [7].

Various technologies are developed to give maximum autonomy to the future crew, but all monitoring data will be sent to Earth for analysis to organize the operation and assist the astronauts. Spaceship France team has imagined a methodology base on the application of human factors analysis methods to make it possible to challenge operations envisaged in order to improve them and to reduce the risk of stress and high mental load for astronauts and ground controllers, so hence the risk of operational errors.

2 Methodology to Help Definition of Surface Operations Taking into Account Human Factors

Spaceship France team has defined steps to analyze, test and improve lunar and Martian operational scenarios:

- Analyze existing human spaceflight operations documentation;
- Drawn inspiration from satellite operations;
- Propose lunar and Martian surface operational scenarios;
- Apply human factors methods to analyze and improve operational procedures;
- Tests operational procedures in nominal and non-nominal situation in a simulation dome;
- Use data collected during the tests to improve procedures and the methodology.

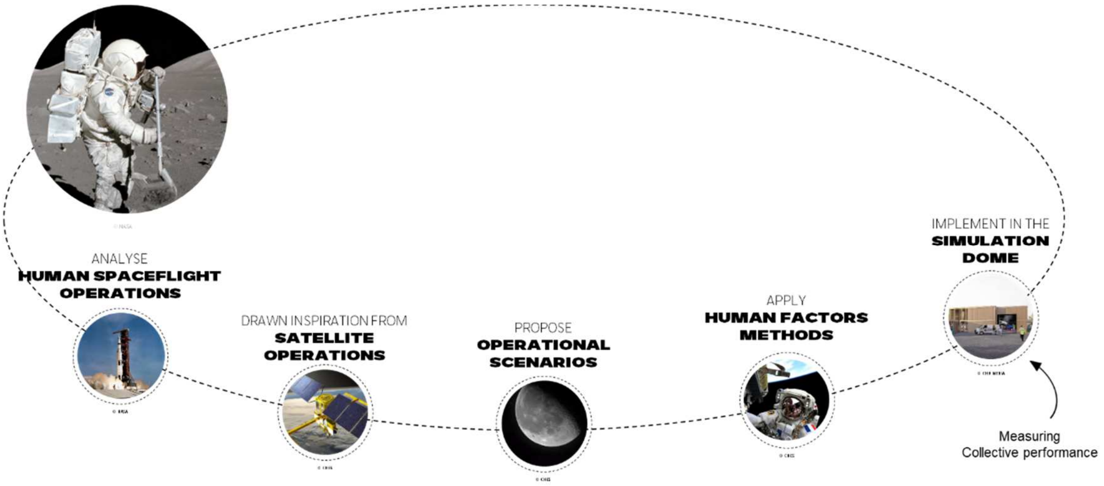


Fig. 2. CNES’s Methodology to Help Definition of Surface Operations Taking into Account Human Factors.

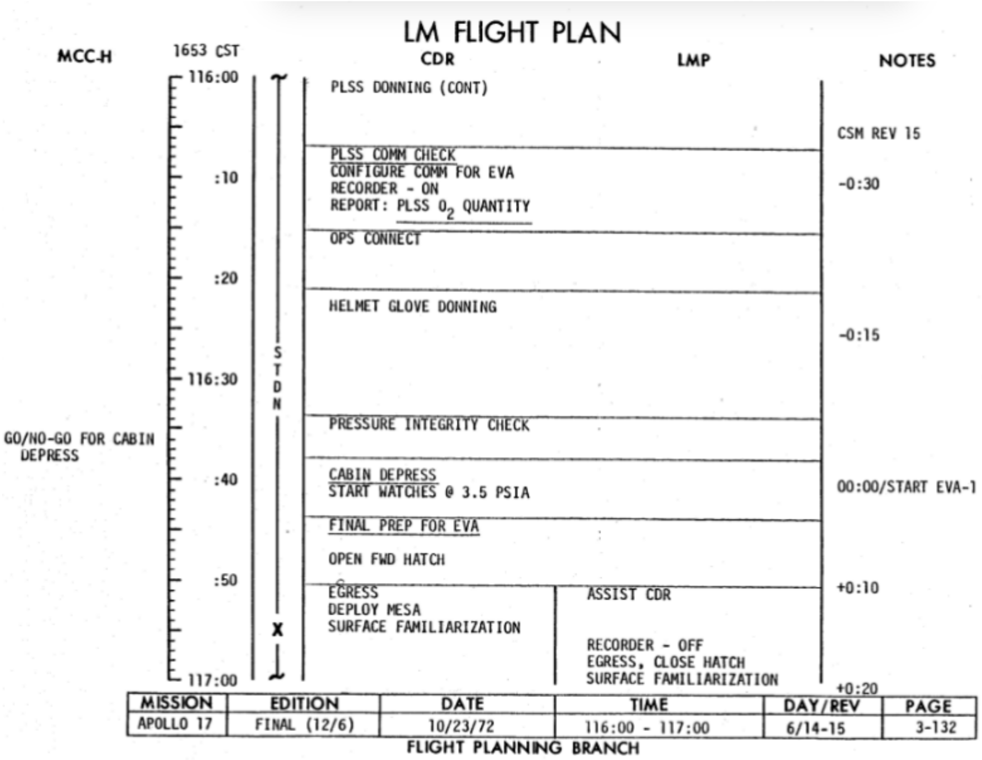
To develop the methodology, concrete case study was used: the collection of geological samples from the Moon's surface.

2.1 Analyzing Human Spaceflight Operations Documentation

To understand human spaceflight concepts of operations and use best practices from previous extravehicular activities, time was devoted to analyzing operational documentation and reports of missions.

2.1.1 Apollo 17 Mission

Apollo missions provide a wealth of information on the execution of EVA activities and on the interaction between astronauts and MCC (Mission Control Center). For geological sample collection activities, documentation from Apollo 17 mission was used [8-9]. Reconstitution of the mission as it occurred in 1972 provide the real time communication from space-to-ground audio and all on-board recorder audio. Complemented by the flight plan in the lunar surface journal of the mission (cf. Fig. 3), they allow us to model all stages of the activity, with details of operations (cf. Fig. 4). A detailed sequence was established from the “EVA planning with Houston” stage to the “EVA debriefing with Houston” stage (cf. APPENDIX A).



LM FLIGHT PLAN

MCC-H | 1653 CST | CDR | LMP | NOTES

116:00
PLSS DONNING (CONT)

CSM REV 15

PLSS COMM CHECK
CONFIGURE COMM FOR EVA
RECORDER - ON
REPORT: PLSS O_2 QUANTITY

:10 -0:30

OPS CONNECT

:20

HELMET GLOVE DONNING

-0:15

116:30

S T D N

PRESSURE INTEGRITY CHECK

GO/NO-GO FOR CABIN DEPRESS

:40

CABIN DEPRESS
START WATCHES @ 3.5 PSIA

00:00/START EVA-1

FINAL PREP FOR EVA

OPEN FWD HATCH

:50

EGRESS
DEPLOY MESA
SURFACE FAMILIARIZATION

ASSIST CDR

RECORDER - OFF
EGRESS, CLOSE HATCH
SURFACE FAMILIARIZATION

+0:10

X

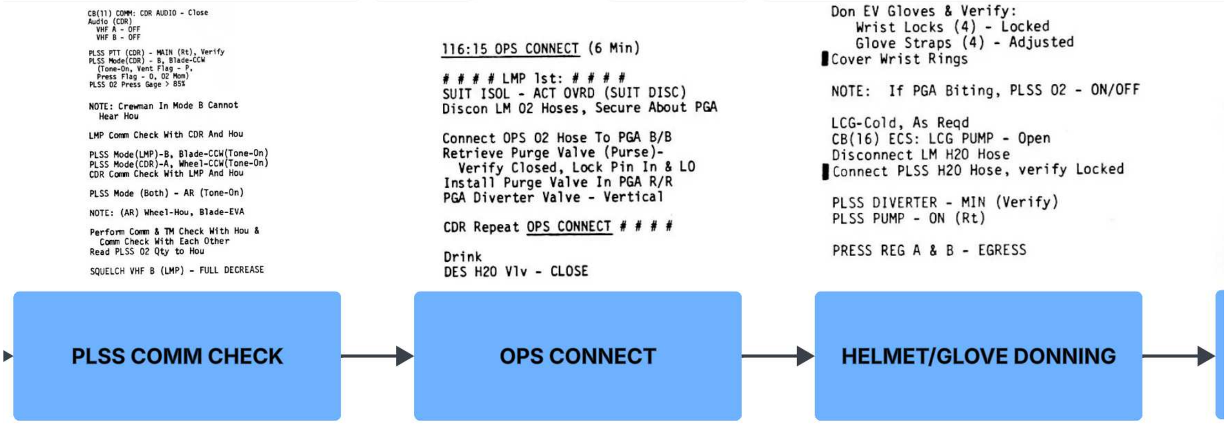
117:00

+0:20

MISSION	EDITION	DATE	TIME	DAY/REV	PAGE
APOLLO 17	FINAL (12/6)	10/23/72	116:00 - 117:00	6/14-15	3-132

FLIGHT PLANNING BRANCH

Fig. 3. Detail of Apollo 17 flight plan [10].



CB(11) COMM: CDR AUDIO - Close
Audio (CDR)
  VHF A - OFF
  VHF B - OFF

PLSS PTT (CDR) - MAIN (Rt), Verify
PLSS Mode(CDR) - B, Blade-CCW
  (Tone-On, Vent Flag - P,
  Press Flag - 0, O2 Mom)
PLSS O2 Press Gage > 85%

NOTE: Crewman In Mode B Cannot
  Hear Hou

LMP Comm Check With CDR And Hou

PLSS Mode(LMP)-B, Blade-CCW(Tone-On)
PLSS Mode(CDR)-A, Wheel-CCW(Tone-On)
CDR Comm Check With LMP And Hou

PLSS Mode (Both) - AR (Tone-On)

NOTE: (AR) Wheel-Hou, Blade-EVA

Perform Comm & TM Check With Hou &
  Comm Check With Each Other
Read PLSS O2 Qty to Hou

SQUELCH VHF B (LMP) - FULL DECREASE

116:15 OPS CONNECT (6 Min)

LMP 1st: # # #
SUIT ISOL - ACT OVRD (SUIT DISC)
Discon LM O2 Hoses, Secure About PGA

Connect OPS O2 Hose To PGA B/B
Retrieve Purge Valve (Purse)-
  Verify Closed, Lock Pin In & LO
Install Purge Valve In PGA R/R
PGA Diverter Valve - Vertical

CDR Repeat OPS CONNECT # # # #

Drink
DES H2O Vlv - CLOSE

Don EV Gloves & Verify:
  Wrist Locks (4) - Locked
  Glove Straps (4) - Adjusted
Cover Wrist Rings

NOTE: If PGA Biting, PLSS O2 - ON/OFF

LCG-Cold, As Reqd
CB(16) ECS: LCG PUMP - Open
Disconnect LM H2O Hose
Connect PLSS H2O Hose, verify Locked

PLSS DIVERTER - MIN (Verify)
PLSS PUMP - ON (Rt)

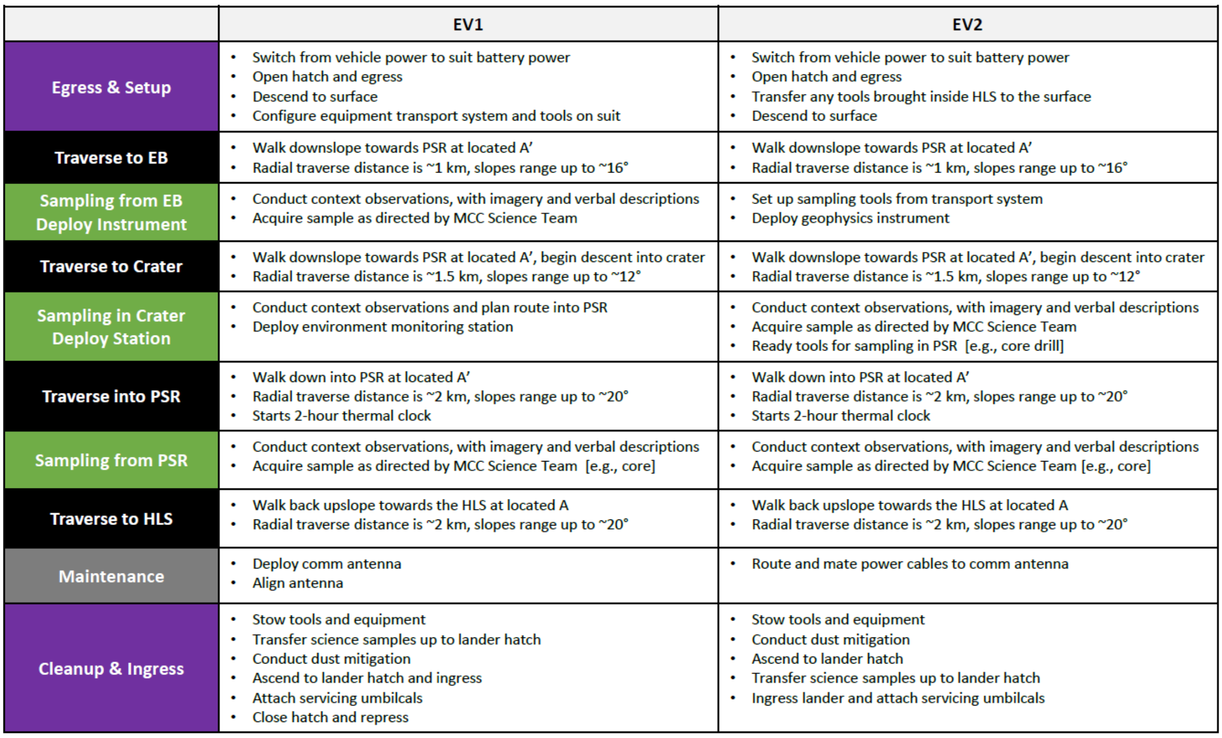
PRESS REG A & B - EGRESS

Fig. 4. Detail of modeled Apollo 17 operation plan. Each stage is connected to corresponding operational steps.

2.1.2 *Artemis Documentation*

Artemis documentation provide references and recommendations to design the future lunar and Martian human spaceflight operations. For the moment, no flight plan nor mission profile are defined. Notional EVAs are used to develop a concept of operations. Following documents have been used to model Artemis surface operations to collect geological samples:

- Document *Exploration EVA system concept of operations* "captures the xEVA concepts of operations for a wide range of destinations" for Artemis program, particularly for lunar surface operations [11]. Document "Exploration EVA System Concept of Operations Summary for Artemis Phase 1 Lunar Surface Mission" provides a list of the main operational stages to be executed by two astronauts during the first Artemis surface mission (cf. Fig. 5) [12].

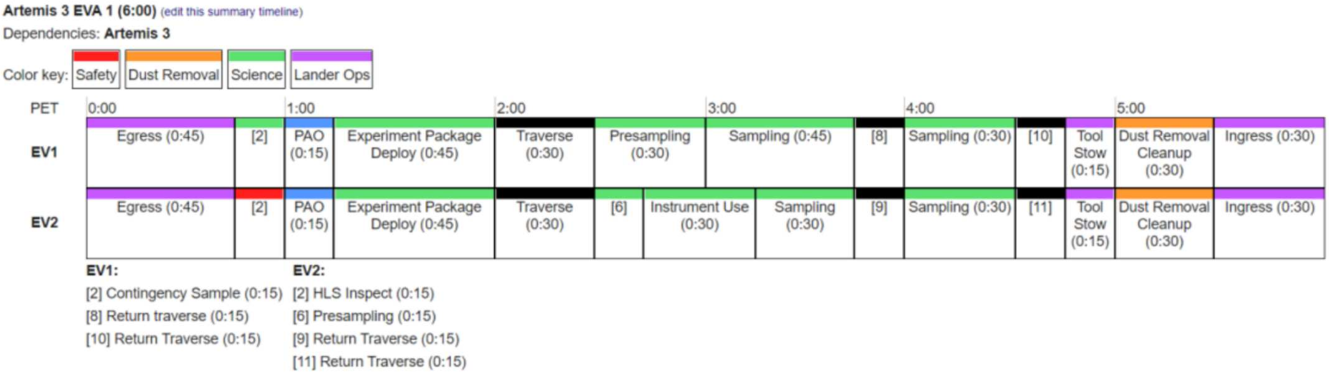


	EV1	EV2
Egress & Setup	• Switch from vehicle power to suit battery power • Open hatch and egress • Descend to surface • Configure equipment transport system and tools on suit	• Switch from vehicle power to suit battery power • Open hatch and egress • Transfer any tools brought inside HLS to the surface • Descend to surface
Traverse to EB	• Walk downslope towards PSR at located A' • Radial traverse distance is ~1 km, slopes range up to ~16°	• Walk downslope towards PSR at located A' • Radial traverse distance is ~1 km, slopes range up to ~16°
Sampling from EB Deploy Instrument	• Conduct context observations, with imagery and verbal descriptions • Acquire sample as directed by MCC Science Team	• Set up sampling tools from transport system • Deploy geophysics instrument
Traverse to Crater	• Walk downslope towards PSR at located A', begin descent into crater • Radial traverse distance is ~1.5 km, slopes range up to ~12°	• Walk downslope towards PSR at located A', begin descent into crater • Radial traverse distance is ~1.5 km, slopes range up to ~12°
Sampling in Crater Deploy Station	• Conduct context observations and plan route into PSR • Deploy environment monitoring station	• Conduct context observations, with imagery and verbal descriptions • Acquire sample as directed by MCC Science Team • Ready tools for sampling in PSR [e.g., core drill]
Traverse into PSR	• Walk down into PSR at located A' • Radial traverse distance is ~2 km, slopes range up to ~20° • Starts 2-hour thermal clock	• Walk down into PSR at located A' • Radial traverse distance is ~2 km, slopes range up to ~20° • Starts 2-hour thermal clock
Sampling from PSR	• Conduct context observations, with imagery and verbal descriptions • Acquire sample as directed by MCC Science Team [e.g., core]	• Conduct context observations, with imagery and verbal descriptions • Acquire sample as directed by MCC Science Team [e.g., core]
Traverse to HLS	• Walk back upslope towards the HLS at located A • Radial traverse distance is ~2 km, slopes range up to ~20°	• Walk back upslope towards the HLS at located A • Radial traverse distance is ~2 km, slopes range up to ~20°
Maintenance	• Deploy comm antenna • Align antenna	• Route and mate power cables to comm antenna
Cleanup & Ingress	• Stow tools and equipment • Transfer science samples up to lander hatch • Conduct dust mitigation • Ascend to lander hatch and ingress • Attach servicing umbilcals • Close hatch and repress	• Stow tools and equipment • Conduct dust mitigation • Ascend to lander hatch • Transfer science samples up to lander hatch • Ingress lander and attach servicing umbilcals

Fig. 5. Notional Design Reference EVA for xEVA Con Ops Development [12].

- Document *xEVA Flight Operations: Preparing for Lunar EVA Training and Execution* provides recommendations to design scenarios for surface operations and to organize tests of the procedures. A notional chronology of operational steps for Artemis 3 (cf. Fig. 6) [13].

2



Artemis 3 EVA 1 (6:00) (edit this summary timeline)
Dependencies: **Artemis 3**

Color key: 🟥 Safety 🟧 Dust Removal 🟩 Science 🟪 Lander Ops

PET 0:00 1:00 2:00 3:00 4:00 5:00

EV1 Egress (0:45) | [2] | PAO (0:15) | Experiment Package Deploy (0:45) | Traverse (0:30) | Presampling (0:30) | Sampling (0:45) | [8] | Sampling (0:30) | [10] | Tool Stow (0:15) | Dust Removal Cleanup (0:30) | Ingress (0:30)

EV2 Egress (0:45) | [2] | PAO (0:15) | Experiment Package Deploy (0:45) | Traverse (0:30) | [6] | Instrument Use (0:30) | Sampling (0:30) | [9] | Sampling (0:30) | [11] | Tool Stow (0:15) | Dust Removal Cleanup (0:30) | Ingress (0:30)

EV1:
[2] Contingency Sample (0:15)
[8] Return traverse (0:15)
[10] Return Traverse (0:15)

EV2:
[2] HLS Inspect (0:15)
[6] Presampling (0:15)
[9] Return Traverse (0:15)
[11] Return Traverse (0:15)

Fig. 6. Summary timeline for Artemis 3 [13].

- Document *Extravehicular Activity and Human Surface Mobility Program (EHP): Integrated Concept of Operations (ConOps)* provides a detail of operational steps for surface operation envisaged for Artemis missions. They are gathered in DRMs (Design Reference Mission) with further EHP level detail (cf. Fig. 7) [14]. These DRMs can be organized to help build a complete operational scenario for geological sample collection (See APPENDIX B).

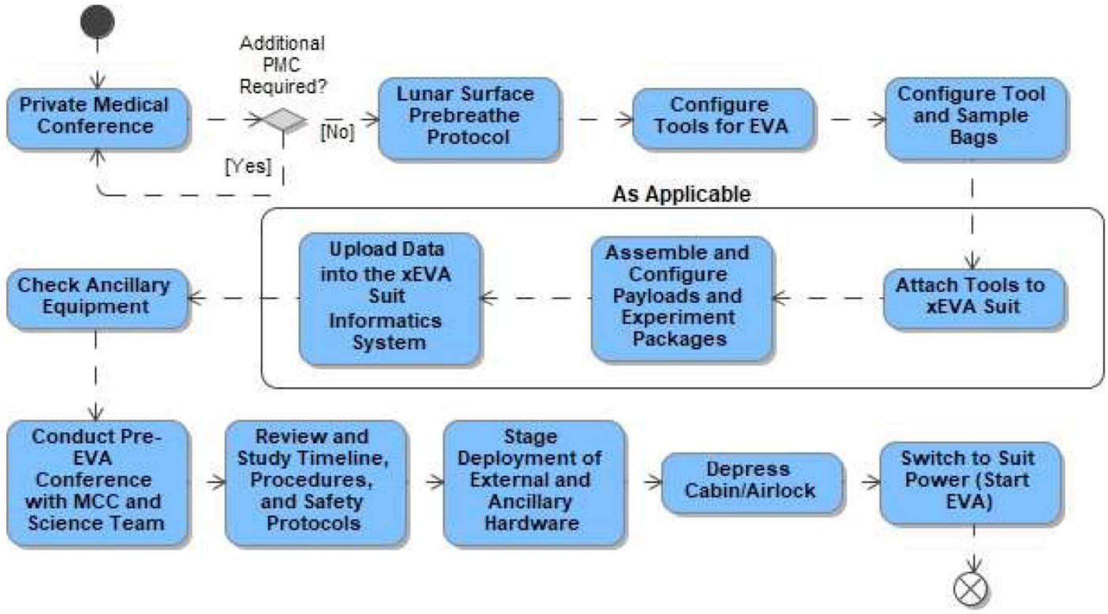


Fig. 7. Example of DRM – DRM 3 EVA PREP AND PREBREATHE [14].

Thank to this documentation, a detailed sequence was established from the “Road-to EVA” stage to the “Post EVA Operations” stage for lunar surface operations (cf. APPENDIX C) given the details for operational steps for each stage (cf. Fig. 8).

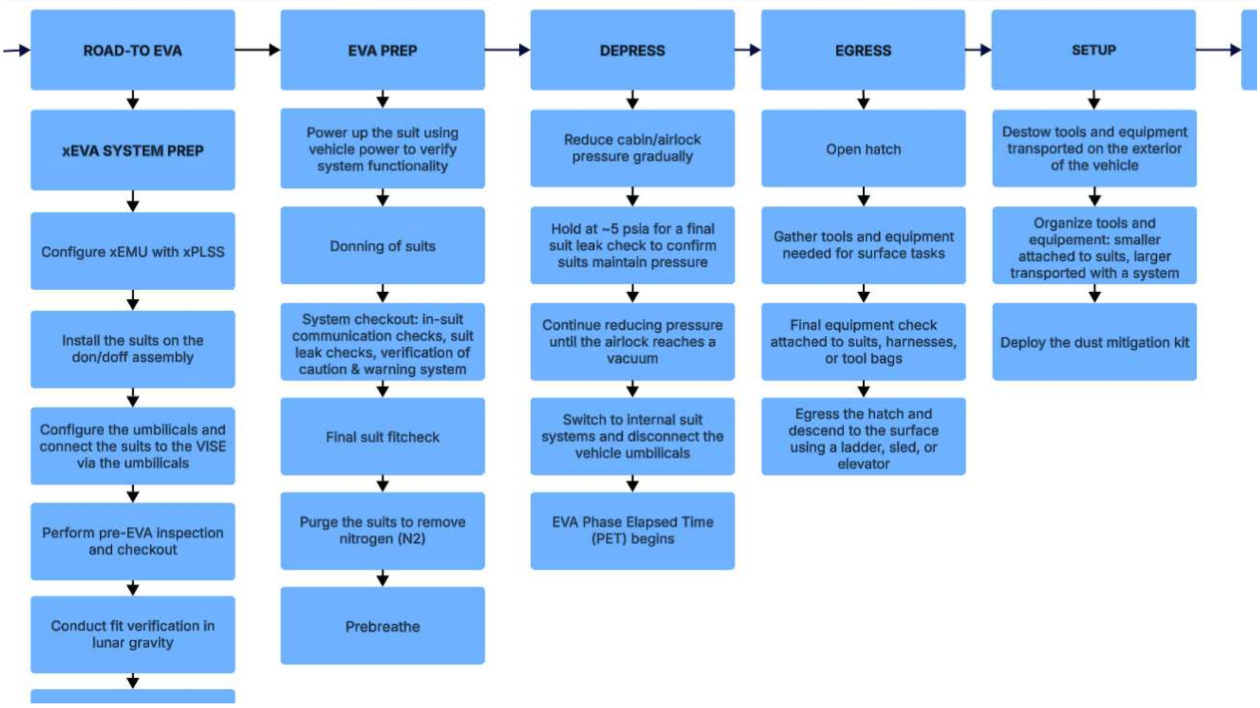


Fig. 8. Detail of modeled Artemis operation plan. Each stage is connected to corresponding operational steps.

2.2 *Drawn Inspiration from Satellite Operations*

Paper *NASA's Identified Risk of Adverse Outcomes due to Inadequate Human Systems Integration Architecture* concludes that “As future missions move beyond LEO, first to the Moon and eventually to Mars, NASA needs to develop a new HSIA [Human-Systems Integration Architecture] that increases the crew’s capability to execute timecritical procedures and respond to safety-critical events without immediate support from the ground" [15]. Authors shows particularly decreasing of ground support as communication delay is increasing (cf. Fig. 9).

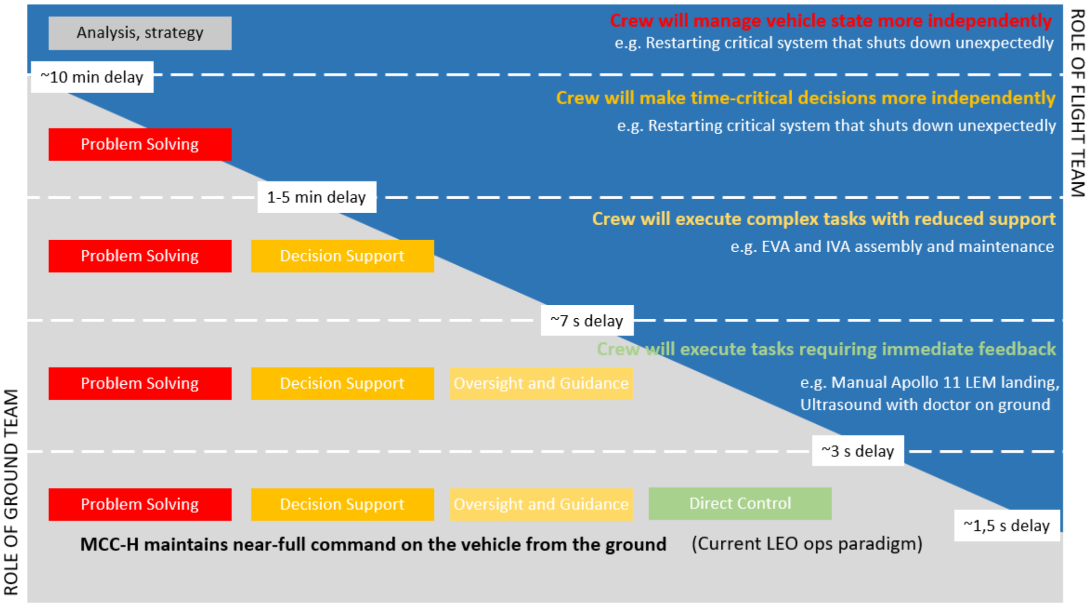


Fig. 9. Ground-to-onboard shift of safety-critical operations with increasing roundtrip communication delays. Time delays are notional. [15] (diagram copied from the original paper)

Best practices from satellite and rover operations can help to adapt concept of operations for human lunar and Martian flights. The constraints of this type of operations from Earth are in line with the future surface missions:

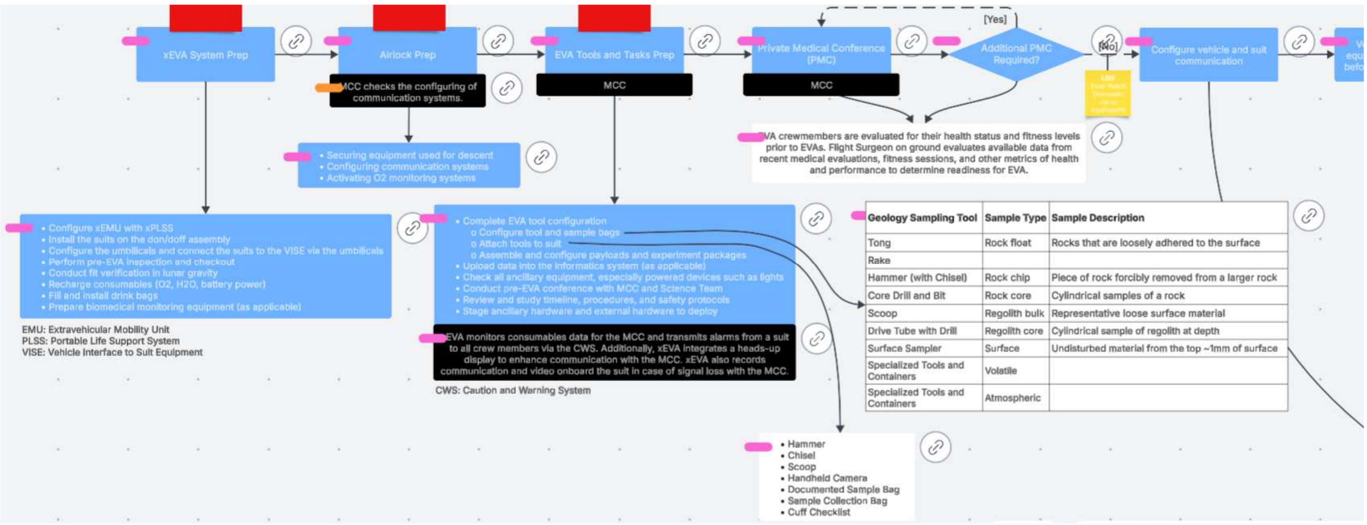
- No permanent communication with the flight segment: data reception for monitoring and transmission for command are always deferred;
- Limited command of the flight segment: the operation plan is uploaded few times a day. Bandwidth does not allow the transmission of a large amount of data;
- High degree of autonomy for the flight segment, as there are no real-time operations, emergencies are dealt with off-line;
- No direct maintenance: in the event of an anomaly, a formal troubleshooting, analysis and resolution process is carried out.

These best practices are inspiring and Spaceship France team is working with CNES operational teams to transpose them for future lunar and Martians mission. But they have their limits, and we need to find the right balance and the right tools to give astronauts maximum autonomy while providing maximum support from Earth.

2.3 *Proposing Operational Scenarios*

Operational procedures are modeled in a graphical tool that lets you grasp all the steps at a glance (detail is presented in Fig. 10). It also allows you to associate references for each step: details of the procedure to be carried out and the origin from which it was drawn up (for example, a procedure from the Apollo 17 mission). For the time being, everything is implemented by hand and a formalism has been adopted, necessary for the understanding of the various users, and to identify missing elements:

- ARTEMIS Origin of the procedure step;
- 🔗 Link to the reference document;
- 🟦 Crew procedure step;
- ⬛ Mission Control Center (MCC) procedure step
- 🟥 Procedure step to be completed;
- 🟨 Architecture element to operate.



MCC checks the configuring of communication systems.

- Securing equipment used for descent
- Configuring communication systems
- Activating O2 monitoring systems

- Configure xEMU with xPLSS
- Install the suits on the don/doff assembly
- Configure the umbilicals and connect the suits to the VISE via the umbilicals
- Perform pre-EVA inspection and checkout
- Conduct fit verification in lunar gravity
- Recharge consumables (O2, H2O, battery power)
- Fill and install drink bags
- Prepare biomedical monitoring equipment (as applicable)

EMU: Extravehicular Mobility Unit
PLSS: Portable Life Support System
VISE: Vehicle Interface to Suit Equipment

- Complete EVA tool configuration
  - Configure tool and sample bags
  - Attach tools to suit
  - Assemble and configure payloads and experiment packages
- Upload data into the informatics system (as applicable)
- Check all ancillary equipment, especially powered devices such as lights
- Conduct pre-EVA conference with MCC and Science Team
- Review and study timeline, procedures, and safety protocols
- Stage ancillary hardware and external hardware to deploy

EVA monitors consumables data for the MCC and transmits alarms from a suit to all crew members via the CWS. Additionally, xEVA integrates a heads-up display to enhance communication with the MCC. xEVA also records communication and video onboard the suit in case of signal loss with the MCC.

CWS: Caution and Warning System

EVA crewmembers are evaluated for their health status and fitness levels prior to EVAs. Flight Surgeon on ground evaluates available data from recent medical evaluations, fitness sessions, and other metrics of health and performance to determine readiness for EVA.

Geology Sampling Tool	Sample Type	Sample Description
Tong	Rock float	Rocks that are loosely adhered to the surface
Rake		
Hammer (with Chisel)	Rock chip	Piece of rock forcibly removed from a larger rock
Core Drill and Bit	Rock core	Cylindrical samples of a rock
Scoop	Regolith bulk	Representative loose surface material
Drive Tube with Drill	Regolith core	Cylindrical sample of regolith at depth
Surface Sampler	Surface	Undisturbed material from the top ~1mm of surface
Specialized Tools and Containers	Volatile	
Specialized Tools and Containers	Atmospheric	

- Hammer
- Chisel
- Scoop
- Handheld Camera
- Documented Sample Bag
- Sample Collection Bag
- Cuff Checklist

Fig. 10. Detail of modeled procedure for geological sample collection.

Procedures for ISS can help to complete the procedure for geological sample collection, for example to carry pre-breathing steps or to operate the hatch. Other reference documents can be used to manage particular steps, for example:

- Documents *Lunar Dust Mitigation: A Guide and Reference* and *An update on NASA's lunar dust mitigation strategy* can help determine steps to manage dust in order to avoid contamination of the lunar habitat at the end of the EVA [16-17];
- Documents *Modeling a 15-min extravehicular activity prebreathe protocol using NASA 's exploration atmosphere (56.5 kPa/34% O2)* and *NASA Space flight human-system standard: Volume 1: Crew health* can help carry steps for pre-breath protocol before spacesuit donning [18-19];
- Information on the Lunar Terrain Vehicle is available on NASA website [20].

2.4 *Applying Human Factors Methods*

All human factors analysis methods are described in the reference work *Human factors methods: A practical guide for engineering and design, 2nd edition* [21]. Currently, two methods are used to analyze and to build operational scenarios.

2.4.1 *Hierarchical Task Analysis (HTA)*

Apollo 17 and notional Artemis operations models were built using human factor Hierarchical Task Analysis (HTA) method. Same for the lunar scenario to collect geological sample. Document *Hierarchical task analysis: Developments, applications, and extensions* explains that “The three main principles governing the analysis were stated as follows [22]:

1. At the highest level we choose to consider a task as consisting of an operation and the operation is defined in terms of its goal. The goal implies the objective of the system in some real terms of production units, quality or other criteria.

2. The operation can be broken down into sub-operations each defined by a sub-goal again measured in real terms by its contribution to overall system output or goal, and therefore measurable in terms of performance standards and criteria.

3. The important relationship between operations and sub-operations is really one of inclusion; it is a hierarchical relationship. Although tasks are often procedural, i.e. the sub-goals must be achieved in sequence, this is not always the case.

The end result of an HTA is a detailed description of a task or activity workflow (APPENDIX A and B).

2.4.2 *Task Decomposition*

For the lunar scenario to collect geological sample, the Task Decomposition method is used to obtain an exhaustive description of the procedural step. For each task, following information have to be filled:

- Task step description;
- Location to indicate where the task is executed;
- Displays used to provide information;

- Communications means used;
- Decisions required during the task;
- Probable errors which can happen during the task;
- Error consequences.

This information is supplemented by 3 criteria to assess whether the task can be carried out serenely by a single person, or whether special precautions need to be taken (adding an operator, support from a control center, more checks when carrying out the task, etc.):

- **Complexity**: refers to the inherent structure of the task, including the number of steps, interactions, and dependencies between elements. The three levels for Complexity are presented in Table 1.

Table 1. Levels for Complexity criterion

Low	Medium	High
The task involved a single action.	The task involved multiple checks or installations.	The task involved multiple configurations.

- **Difficulty:** describes how challenging the task is for the person performing it. It depends on cognitive load, required skills, physical demands, and prior knowledge. The three levels for Difficulty are presented in Table 2.

Table 2. Levels for Difficulty criterion

Low	Medium	High
Prepare and verify.	Configure, collect and clean.	Experiment.

- **Criticality:** measures the potential consequences of task failure. The three levels for Criticality are presented in Table 3.

Table 3. Levels for Criticality criterion

<table>
<tr><th></th><th>Low</th><th>Medium</th><th>High</th></tr>
<tr><td>Ensure astronaut safety</td><td>■</td><td>The task is performed to ensure astronaut safety (indirectly).</td><td>The task is performed to ensure astronaut safety.</td></tr>
<tr><td rowspan="2">Ensure mission success</td><td rowspan="2">The task is performed to ensure mission success, but the systems would be checked on the day of the EVA.
The task is performed to ensure mission success (indirectly).</td><td>The task is performed to ensure mission success.</td><td>■</td></tr>
<tr><td colspan="2">The task is performed to ensure mission success and may impact astronaut safety.</td></tr>
</table>

This method is applied for each task of the scenario. Table 4 shows an example of Task Decomposition analysis for Airlock Preparation task.

Table 4. Example of Task Decomposition analysis for Airlock Preparation task

Task step description: Prepare the airlock for the EVA.	**Complexity:** High. The task involved multiple checks and configurations.
Location: Airlock.	**Difficulty:** Low.
Displays used: Equipment and airlock system with its display.	**Criticality:** Medium. The task is performed to ensure astronaut safety, but the systems would be verified on the EVA day.
Communications (ref. Artemis/Apollo)**:** Crew ↔ MCC/IV.	**Probable errors:** Incomplete or incorrect preparation.
Decisions required: Confirm airlock readiness.	**Error consequences:** Missing or malfunctioning equipment. Mission compromised, risk to astronaut safety.

2.5 *Implementing in the Simulation Dome*

Once scenario is written, the goal is to test it in the SENS facilities [23]. SENS is the "Centre de simulation neurosensorielle et environnementale" (Neurosensory and Environmental Simulation Center), a simulation center that places healthcare professionals in extreme conditions (climate, snow, high heat, exposure to complicated interventions, noise, smell of ash), preparing them for the worst so they can be as operational as possible (cf. Fig. 11). The means can also be used to tests lunar and Martian surface operations.

Fig. 11. Pictures of SENS facilities.

Objectives are to measure the collective performance and to improve the procedures starting again the methodology analysis. It is planned to play the nominal scenario and degraded cases. For our first experiment with geological sample collection scenario, two degraded cases will be tested:

- Degrade case 1:
  - Communication disturbances;
  - Dust accumulation on visor and gloves;
  - Glare on visor.
- Degrade case 2:
  - Forgotten or damaged tool;
  - Extended EVA: need to save energy.

3 Discussions

The scenarios are currently being developed, and we are working with the Spaceship France medical team to integrate collective measurement during the tests. The next major step will take place in the summer of 2025. We will be running the first tests in SENS and experimenting with data collection and analysis to improve our scenarios and our method.

Work continues on improving procedures, identifying other human factors-based methods for improving scenarios and making them more relevant. A first list of recommendations and warnings have to be taken into account to implement scenarios:

- Apollo 17 mission has taught us that MCC must continuously monitor and follow the task descriptions from the astronauts ("copy that"), intervening if MCC needs additional information, if the astronauts forget something, or if there is a problem [24].
- Document *Exploration EVA system concept of operations* has taught us that Intra-Vehicular astronaut or system (in the habitat or in the rover) must provide a local support to efficiently handle the large amount of information and tasks involved in actively steering an EVA [11]. The xEVA System must include:
  - Means of communication with the MCC and the EVA - both voice and text;
  - Display of real-time and previously acquired video and still images of the crew;
  - Display of tracking procedures and maps for all those involved in the EVA;
  - Real-time EVA timeline management and automated analysis;
  - Monitoring of suit data and telemetry;
  - Access to information relevant to the execution of the EVA (i.e. images, sample notes, videos, locations of interest, etc.)

  - Real-time updating of information useful for performing EVA (i.e. procedures, images, notes, etc.);
  - Real-time updating of procedures;
  - Dynamic prioritization of scientific objectives;
  - Annotation of images;
  - Display of crew and equipment location;
  - Display of actual and planned traverses with information on distance and travel time;
  - Creation and display of augmented reality cues and visuals;
  - Display of previously acquired, real-time in situ instrument and sensor data.
- During Martian EVA, the Intra-Vehicular crewmember will be tasked with a monumental amount of cognitive burden previously performed by dedicated teams of numerous people on Earth. NASA is developing the Personalized EVA Informatics and Decision Support (PersEIDS) system to support the time-sensitive, safety-critical decisions that must be made by crew on the surface of Mars [25]. PersEIDS operates as a companion software component of EVA mission scheduling and timeline management software, e.g., Maestro or Playbook. The software is designed to leverage observed biomedical data during previous missions and analog studies to project the biomedical state of the crewmember/suit system over any given EVA timeline.

We are also in the process of drawing on the experience of CNES operational teams working for LEO satellites or for the French experiments on Mars rovers. Experience of COMET OPS, a French community of experts in operations and human factors, is also very inspiring [26]. “This group’s activities are centered around sharing experience, thoughts and proposals in the field of operations of said systems to ensure that lessons learnt (feedback) contribute to the evolution of techniques and their acquisition, to the full consideration of the human factor, to compliance with safety rules, to improvement in the service provided, to operational security and to the optimization of ownership costs.” Publications and presentations from previous conferences will help us improve our methodology:

- Training and operational practices [27];
- HUman DEPendability [28];
- Automated operations [29];
- Operations and Operators of the future [30];
- OCAI: The Operations Companion to support decision making of flight control teams [31];
- Interplanetary Mission Operations [32];
- Human factor [33];

We will also look at introducing the HAMSTERS tool into our methodology [34]. “HAMSTERS (Human – centered Assessment and Modelling to Support Task Engineering for Resilient Systems) is a tool-supported task modelling notation for representing human activities in a hierarchical and structured way, with the intention of supporting modelling consistency, coherence and conformity between user tasks and interactive systems”. This tool can also help for the Task Decomposition and the application of human factors methods will be more precise. This will enable us to make the scenarios played out in the SENS installations more relevant.

In, Paper *NASA's Identified Risk of Adverse Outcomes due to Inadequate Human Systems Integration Architecture*, authors estimate that “today, there are 80+ experts on the ground with a combined 600+ years of system-specific experience sitting console and monitoring data, detecting anomalous events, devising plans of action, and overseeing crew procedure execution.” [15] To transfer this expertise, Spaceship France team is working on various tools and concepts:

- Systems that integrate specific expertise to give astronauts greater autonomy, for example a portable geological expert called GeoAssist to select the most interesting samples during EVAs [35];
- A digital assistant based on artificial intelligence called AMAIA (previously called AI4U) to assist astronauts on their journey to the Moon and Mars. Its main functions are: autonomous supervision of the habitat, support and optimization of mission and operations, moral support to astronauts by acting as a companion (countermeasure against the stressful and isolating conditions of life in space) [35];
- Digital twins, for example an “Artificial Intelligence Toolbox for Health” which gather « Digital twin(s)» will be set up to measure astronaut’s vital signs, analyze musculoskeletal behavior, prescribe personalized medication, identify environment risk factors and associated impacts on health, recommend countermeasure exercises adapted to the astronaut [35]; or a digital twin of the Moon to improve simulations, mission preparation and operational support [36];

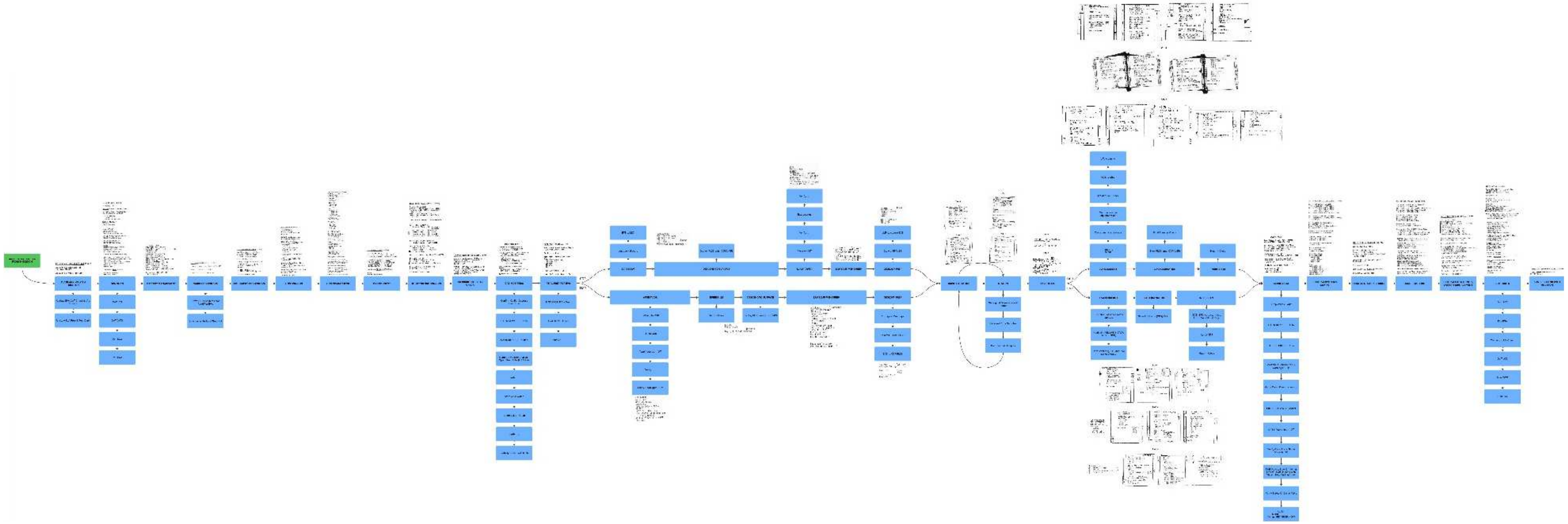
- concepts for remote control centers in a lunar base or pressurized rover.

The aim is to integrate these tools for increasing astronaut autonomy as early as possible in the scenarios, so as to gain rapid feedback from the tests carried out in SENS facilities.

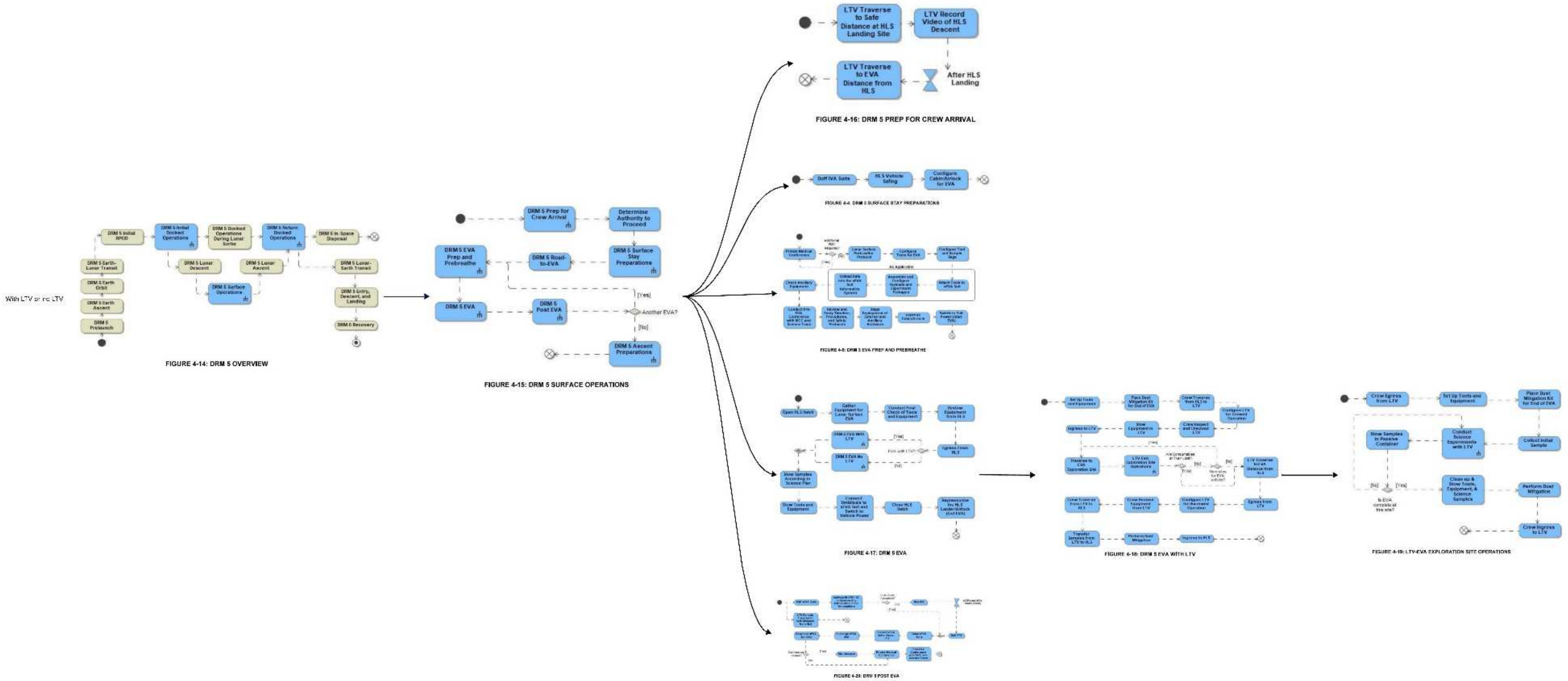
4 Conclusions

Future lunar and Martian missions will be a challenge for crews and ground control operators. Communication delays will prevent real-time support and command/control from the Earth for human spaceflight activities. New concepts of operations have to be found maintaining the collective performances of current operational teams. The Spaceship France team analyzed Apollo and Artemis operations to develop the first elements of a methodology based on human factors methods. This methodology will enable us to imagine future operational scenarios designed to be consistent with the new concepts of operation. Thanks to the SENS facilities, we can close the loop by testing the scenarios and using the test results to improve the scenarios and the methodology itself. Work is continuing to identify other human factors-based methods to improve the scenarios and make them more relevant.

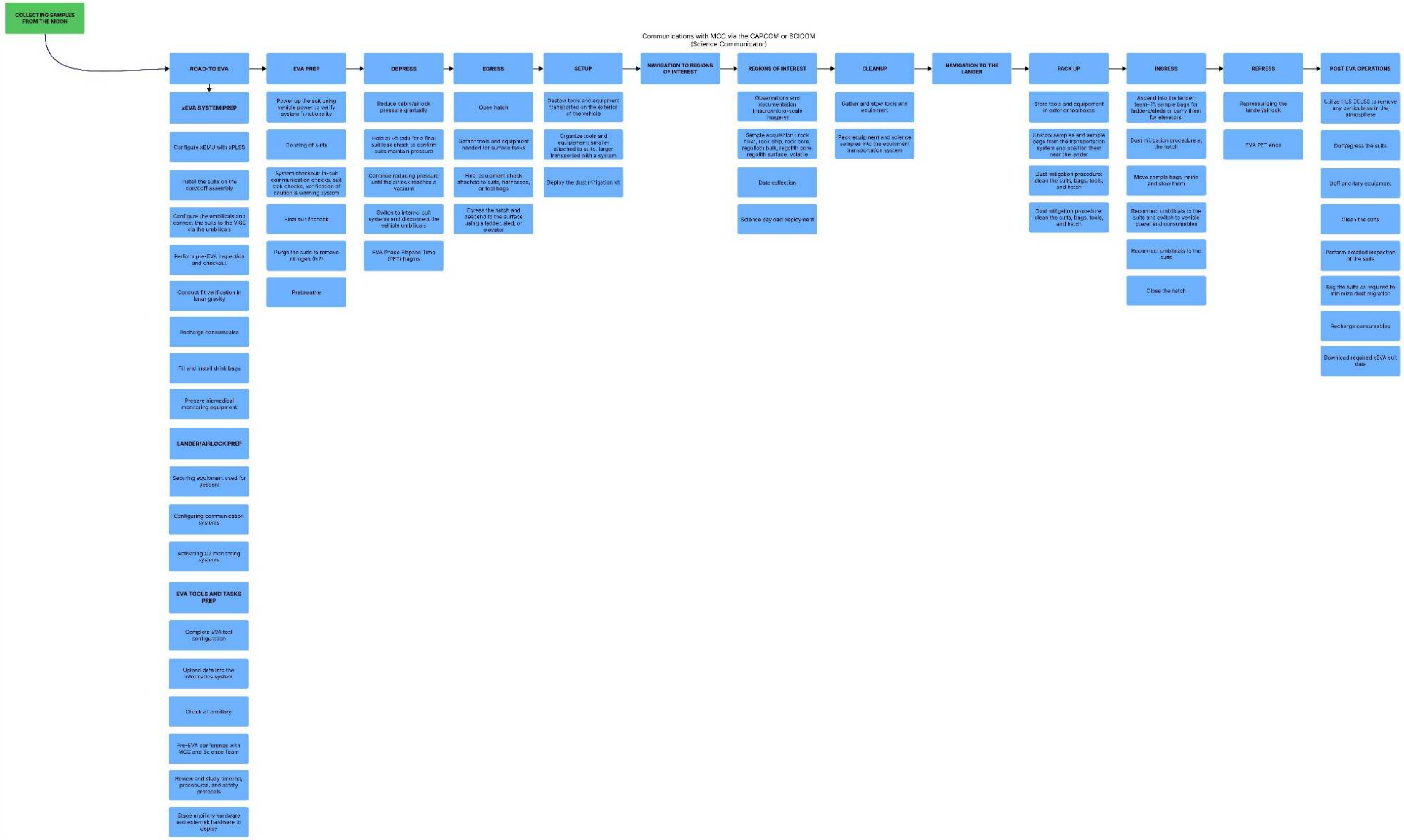
Appendix A – Apollo 17 Steps



Appendix B – Artemis DRMs organization for a geological sample collection scenario



Appendix C – Artemis Steps



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