SpaceOps-2023, ID # 136

Investigations on Lunar Operations Concepts for Human Spaceflight

D. Sabath [1*], G. Soellner [2], M. Wendel[3], T. Mascher [4], D. Kaschubek [5], M. Killian [6], G. Zöschinger [7], C. Hartmann [8], T. Uhlig [9]

[1] *DLR Oberpfaffenhofen, GSOC, 82234 Weßling, Germany, e-mail: dieter.sabath@dlr.de*
[2] *DLR Oberpfaffenhofen, GSOC, 82234 Weßling, Germany, e-mail: gerd.soellner@dlr.de*
[3] *Institute of Astronautics, Technical University of Munich, 85748 Garching, Germany, e-mail: Mareike.Wendel@web.de*
[4] *Institute of Astronautics, Technical University of Munich, 85748 Garching, Germany, e-mail: mascherthomas@gmail.com*
[5] *yuri GmbH, 88074 Meckenbeuren, Germany, daniel.kaschubek@yurigravity.com*
[6] *Institute of Astronautics, Technical University of Munich, 85748 Garching, Germany, m.killian@tum.de*
[7] *DLR Oberpfaffenhofen, GSOC, 82234 Weßling, Germany, e-mail: german.zoeschinger@dlr.de*
[8] *DLR Oberpfaffenhofen, GSOC, 82234 Weßling, Germany, e-mail: carsten.hartmann@dlr.de*
[9] *DLR Oberpfaffenhofen, GSOC, 82234 Weßling, Germany, e-mail: Thomas.Uhlig@dlr.de*

* Corresponding Author

Abstract

In the course of the current decade the return to the Moon is on the agenda of NASA - this time in a joint effort with other space agencies like ESA, CSA and JAXA. The German Space Operations Center (GSOC) as part of DLR is able to bring in their 40 years of experience in human space flight operations into this new endeavour. A study phase together with the TU München has been started some years ago to investigate challenges and necessary operations changes for missions beyond LEO.

This paper provides the results of the investigations on operating the notional lunar infrastructure for human spaceflight in the early 2030s, consisting of the Gateway and medium-sized landing missions to the lunar south pole. The analysis compares different operational concepts of the Gateway, i.e. campaign mode versus continuous mode and provides an overview on the expected setup of the involved control centers on Earth. It is assumed that the major goal of a landing near the lunar south pole is the search for water ice in permanently shadowed regions (PSR). As the PSRs are normally not reachable by astronauts due to the expected low temperature, the operational scenario of a rover searching for water ice in a PSR is laid out and analysed including the necessary human robotic interaction.

This paper summarizes the results of the investigation on this notional scenario. It provides an outlook on the foreseen next steps towards an operations setup around and on the moon including the envisaged European tasks in a planned lunar exploration scenario.

Keywords: (Moon, operations, human spaceflight, robotics, LUNA, excursion)

Acronyms/Abbreviations

BPA	Brine Processing Assembly
CAMRAS	Carbon-dioxide and Moisture Removal Amine Swing-bed
CDRA	Carbon Dioxide Removal Assembly
Col-CC	Columbus Control Center
DEM	Digital Elevation Model
DSL	Deep Space Logistics
DSM	Digital Slope Model
ECLSS	Environmental Control and Life Support System
ESM	European Service Module
GSOC	German Space Operations Center
HECC	Human Exploration Control Center
HLS	Human Landing System
ICPS	Interim Cryogenic Propulsion Stage
LEO	Low Earth Orbit
LLO	Low Lunar Orbit

LOI	Lunar Orbit Insertion
LRU	Lightweight Rover Unit
MCC	Mission Control Center
NRHO	Near Rectilinear Halo Orbit
OGA	Oxygen Generation Assembly
POL	Peak Of Light
PSR	Permanently Shadowed Region
R&D	Rendezvous and Docking
RTG	Radio-Thermal Generator
SCRA	Sabatier CO_2 Reprocessing Assembly
SLS	Space Launch System
SoC	State of Charge
TLI	Trans Lunar Injection
UPA	Urine Processing Assembly
WIL	Water Ice Location

1. Introduction

While putting the main focus on human spaceflight operations in Low Earth Orbit (LEO), i.e. operating ISS/Columbus in partnership with ESA (see [1], [3], [4], [8] and[17]), Col-CC/GSOC has investigated missions and operations scenarios beyond LEO already in the last two decades. This includes scenarios for operations on and around the moon (see [2], [11], [12], [14], [15] and [16]) as well as investigation on challenges of deep space missions in [5], [6] and [10]. Among these are communication aspects including signal delay, operations aspects of station around the moon and on the moon as well as human robotic interaction especially for excursion on the surface of the moon.

These investigations by the experienced team of Col-CC have been mainly performed together with TU Munich in a cooperation concentrating on the operations of future lunar infrastructure. The first results were presented in [11] mainly focused on life support systems, logistics and orbit dynamics of the Gateway and their impact on operations. In the recent years the focus was partly changed to operational problems, i.e. how operations around or on the Moon can be optimized. The main items of investigation were the comparison between campaign mode and continuous mode operations on the Gateway as well as operations scenarios on the lunar south pole. These two topics where chosen because they seem to be the most probable exploration scenarios in this decade in view of available plans of the space agencies.

The assumed lunar infrastructure is closely related to the NASA/ESA/JAXA/CSA Artemis missions but defines own scenarios and setups where appropriate. This allows to analyse different scenarios, look for possible optimization or detect shortcomings of divergent setups.

2. Gateway operations scenario

In the paper on the Gateway architecture presented at IAC 2019 [11], the impacts of different subsystem designs - especially the ECLSS system - as well as the orbit selection for a lunar orbiting space station has been analyses. As explained before, the focus of the investigations of the last years was changed towards operational problems. Hence, in succession of [11] the impacts of the chosen Gateway design on the operations concepts together with the investigation on alternative operations concepts has been investigated.

2.1. Chosen Setup

In [11], a concept of operations for the post assembly phase of this station has been established. Four different setups are developed to cover various infrastructure and operations scenarios. The four scenarios differentiate in their duration and life support system. The first scenario describes a twelve weeks campaign style mission with a regenerative life support system. The second scenario is of the same duration as the first, but uses a non-regenerative life support system. The third and fourth scenario are designed to enable a permanently crewed Gateway, in contrast to the campaign mode missions. Their life support systems are altered as well, creating the third scenario with a regenerative and the fourth with a non-regenerative system. All scenarios include an identical lunar excursion of four weeks for all four crew members. To incorporate a certain redundancy in the logistics scenario two different cargo spacecrafts are chosen for logistic flights, a modified Dragon and a modified Cygnus; details on the spacecrafts are described in [11].

For the Gateway (see Fig. 1) the standard NRHO was chosen to be the most suitable and flexible orbit, not only to act as an intermediate step to the Moon, but also as a communications relay.

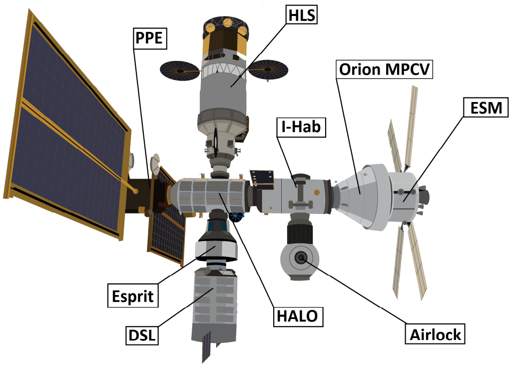


Fig. 1. Lunar Gateway [13]

For the ECLS Systems mentioned above, the following boundary conditions were chosen:

- The Regenerative ECLSS includes a Urine Processing Assembly (UPA) and a Brine Processing Assembly (BPA) which process urine and reduce a minimal amount of lost water enabling long-duration missions without the need for water resupply [14]. The carbon dioxide (CO_2) is removed via a cycle consisting of a Carbon Dioxide Removal Assembly (CDRA) and a Sabatier CO_2 Reprocessing Assembly (SCRA). Inside the SCRA, CO_2 reacts with hydrogen (H_2) in the presence of ruthenium as a catalyst producing methane (CH_4) and water (H_2O). The hydrogen required for this process is produced via the OGA in an electrolysis that also provides oxygen for the crew using the water from the UPA.
- As a non-regenerative system, a CAMRAS based ECLSS was chosen. Besides carbon dioxide removal all components have to be supplied from storage tanks. CAMRAS uses an amine swingbed that is regenerated by the vacuum of space. It absorbs the carbon dioxide as well as humidity from the cabins atmosphere and vents these unwanted compounds into space.

Additionally, the ECLSS calculation includes also the necessary food, drinking water and clothes for the crew. For details on the chosen ECLSS system see [11] and [14].

2.2. Mission Scenarios

As described before two scenarios are investigated for Gateway operations:

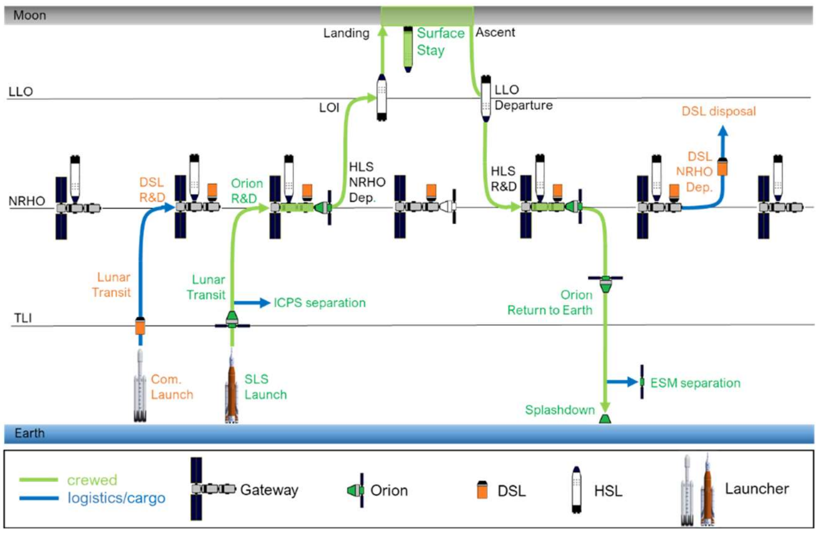


Fig. 2. Flight architecture of the campaign mode

In the campaign mode as shown in Fig. 2 and Fig. 3, one single mission to the Gateway and the Moon will be performed per year. During the rest of the year the Gateway is in an automated and uncrewed mode. In this scenario the HLS is assumed operational in a reusable manner and thus docked to the Gateway. The crew will consist of a total of four astronauts and all four will descent towards the surface during the four week long lunar excursion. This then requires an about three weeks stay onboard the Gateway before and after the excursion. The total mission duration including the flights from and back to Earth will then be about 12 weeks.

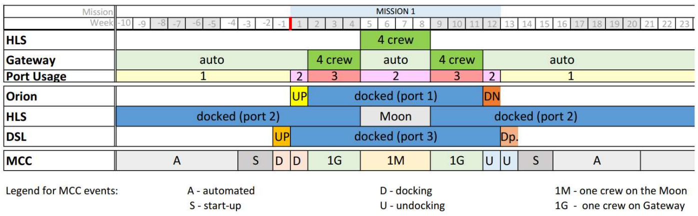


Fig. 3. Sequence of events for the campaign mission mode

In the continuous mode, a permanent human presence onboard the Gateway is assumed. This enables significantly more crew time for science and technical exploration as well as enabling long time experiments necessary for Mars transits. Also transitions from non-automated to automated operations are not needed. Through this, operations can be realized very similar to the ISS. In the continuous mode the total stay on Gateway will be 196 days per crew and the descent towards the lunar surface will be four weeks for each crew. Hence, the model assumes two lunar excursions per year (see Fig. 4). As explained in Fig. 4 and Fig. 5 the lunar excursions are planned for the beginning of each mission to avoid re-adaptation to non-zero gravity in the middle of the mission. During two weeks of handover two Orion crews will be on Gateway creating an overlap between the two missions. In this phase the ECLSS system has to carry a higher load which is bearable according the analysis in [14].

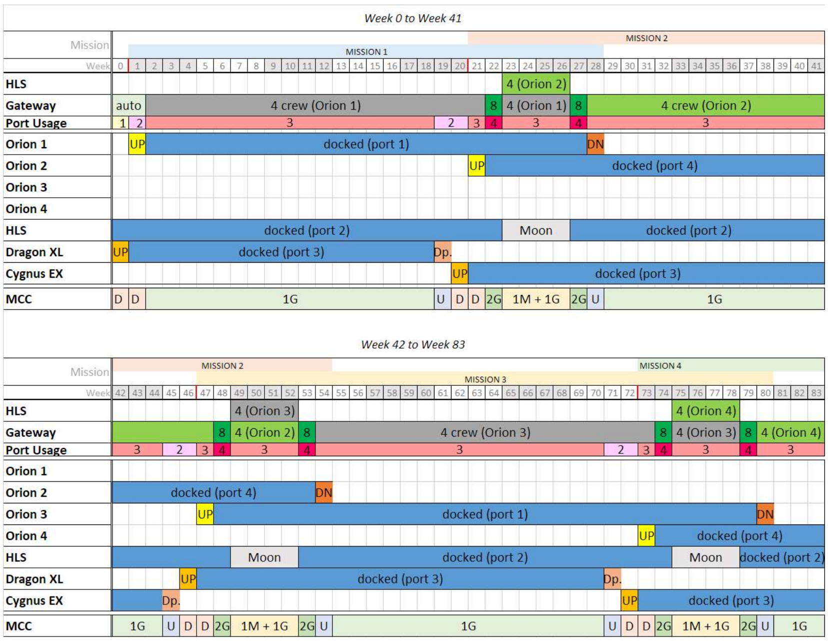


Fig. 4. Sequence of events for the continuous mission mode

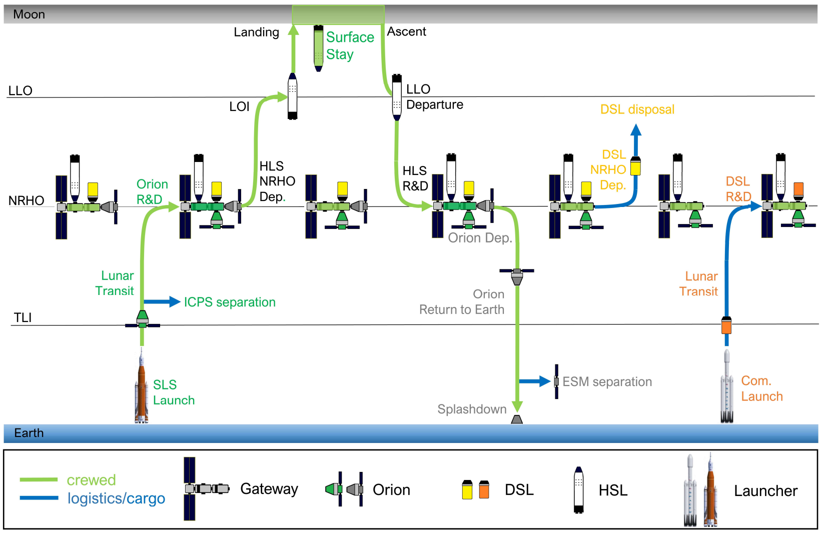


Fig. 5. Flight architecture for the continuous mode

The other sequences and flight architectures are very similar and can be found in [14].

2.3. Results

Considering the boundary conditions, the chosen setup and the mission scenarios described above 4 different types of missions are investigated in this paper:

- Regenerative Continuous Mode
- Non-Regenerative Continuous Mode
- Regenerative Campaign Mode
- Non-Regenerative Campaign Mode

The main focus was on operational impacts on both scenarios including some feasibility checkpoints, e.g. on the necessary supplies for the ECLSS of Gateway and HLS. As shown in Fig. 6 the logistics for crew support wouldn't be a show stopper for a continuous mode because only one additional flight of a resupply vehicle would be necessary according to performed analysis. Nevertheless, to be able to gain the advantages of the continuous mode, the additional effort for a second lunar excursion per year has to be taken into account.

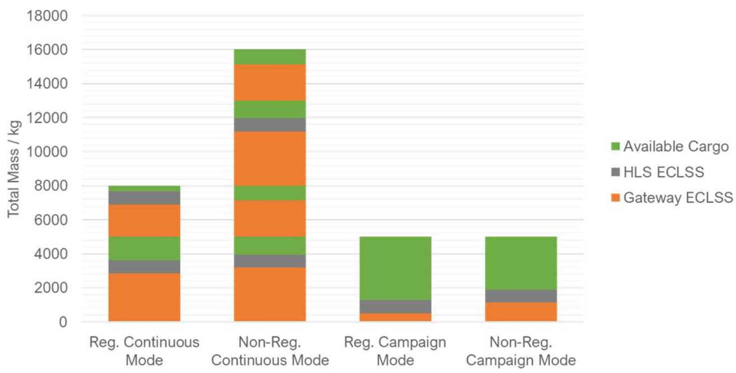


Fig. 6. Total logistic supply mass throughout a year for the four different mission modes

The analysis in [14] shows that the most promising modes are either the regenerative continuous mode or the regenerative campaign mode. The non-regenerative continuous mode needs double the number of resupply vehicle compared to the regenerative mode and is not considered further. Also, the non-regenerative campaign mode reduces the available payload mass compared to regenerative campaign mode. Hence, if the necessary higher initial mass of the regenerative system can be afforded this option is preferred also in view of potential longer missions in a later phase of Moon exploration.

The regenerative campaign mode offers a more feasible logistics with one resupply flight per year and a less demanding operational setup because the teams on ground can focus on one crew, only, which is either on Gateway or on the lunar south pole. On the other side the crew time especially on Gateway is restricted and there will be a lot of time pressure on crew and ground support to fulfil all necessary tasks. In case of a reconfiguration of Gateway to auto mode also during the lunar excursion the ground team and the on-board crew would have to reconfigure the Gateway four times per mission which will increase the workload considerably.

Obviously, the regenerative continuous mode provides more crew time on Gateway and no reconfiguration of the Gateway is necessary because one crew is always on board of Gateway. If a second manned flight to the Moon and a second excursion to the lunar south pole per year would be feasible this mode would offer some advantages compared to two campaign modes per year. Also, the Gateway crew could support the surface crew during their excursion. Nevertheless, the continuous mode needs a second resupply vehicle per year to ensure the crew support, only. It puts a high effort on ground operations to take care on two crews in parallel on Gateway and on the lunar surface. Additionally, during the handover, the ECLSS system has to carry a higher load which is bearable according the analysis in [14].

Summarizing the results above, the campaign mode is preferable as long as the mission sequence is limited to one excursion to the lunar surface per year with a long uncrewed period of the Gateway in-between. If a second excursion per year would be established the continuous mode seems to be the better option. The chosen regenerative ECLSS offers not only also immediate advantages shown above but offers also an improved growth potential with respect to future mission scenarios.

One of the growth potentials of Gateway is an increased support of longer mission towards the lunar south pole. A sample scenario will be analysed in the next chapter.

3. Lunar south pole operations scenario

The next step after Gateway operations will be extended human missions to the lunar surface mainly to the south pole which offers several advantages:

- on the top of several mountains in the south pole area of the Moon like Leibniz or Malapert the shadow phase is quite short, which makes it easier to establish a more long-term mission, i.e. more than two weeks.
- Close by the mountains there are a lot of craters which offer Permanently Shadowed Regions (PSR) offering a very low temperature environment. In some of these craters water ice is expected which will be essential for a human long-term stay on Moon.

Despite this promising environment there are some challenges to overcome before the advantages of these sites can be exploited:

- the temperature in the PSR is too low for human excursion. Hence, robotic exploration is the only possible means which seems to be feasible.
- The altitude difference between the PSR and the locations with nearly permanent sunlight is often very high. Hence, rovers won't be very useful to reach these areas.

3.1. Chosen Landing Site and PSR

Hence, the investigation performed in [15] focused on the challenge to find a PSR reachable by a current technology's rover starting from an area of nearly permanent sun light. Taking into account several boundary conditions like water ice proximity, illumination, landing site slopes and travers feasibility, a landing site with nearby PSR is searched. For this analysis a digital elevation model (DEM) in form of a gridded mesh provided by NASA and a smoothed digital slope model (DSM) is used to find the optimum place for such a mission.

Table 1. Input constraints for landing site selection and traverse optimization

Landing site diameter	Landing site slope	Shadowed days	Distance to POL	Distance to WIL	Traverse slope
1000 m	5°	11 d	10 km	10 km	15°

Taking into account the assumed boundary conditions in Table 1, the known water ice location (WIL, shown in black in Fig. 7) and the peak of lights (POL, shown in white in Fig. 7), the best suited landing site was searched by an iterative process explained in [15].

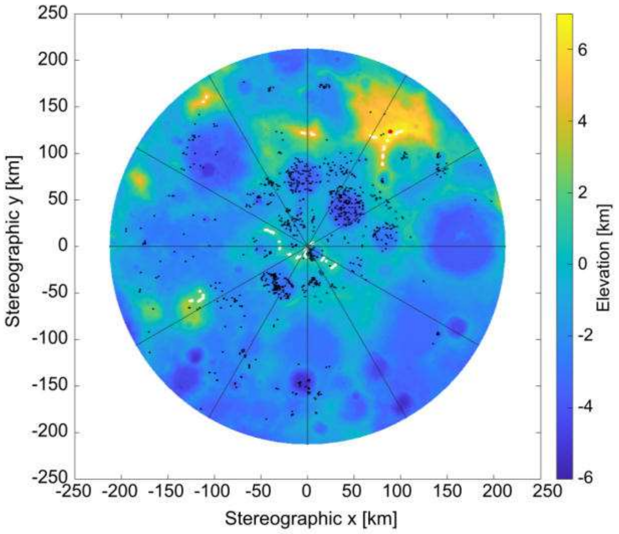


Fig. 7. Elevation model map of the south polar region from 90° S to 83° S latitude with the result of the landing site search (chosen landing site marked in red, WIL marked in black and POL marked in white)

As shown in Fig. 7 the best location for the above described mission is located on the Malapert massive with some PSR nearby (marked by a red dot). Fig. 8 shows a detailed map of the chosen landing site with the traverse put on an elevation model and a slope model.

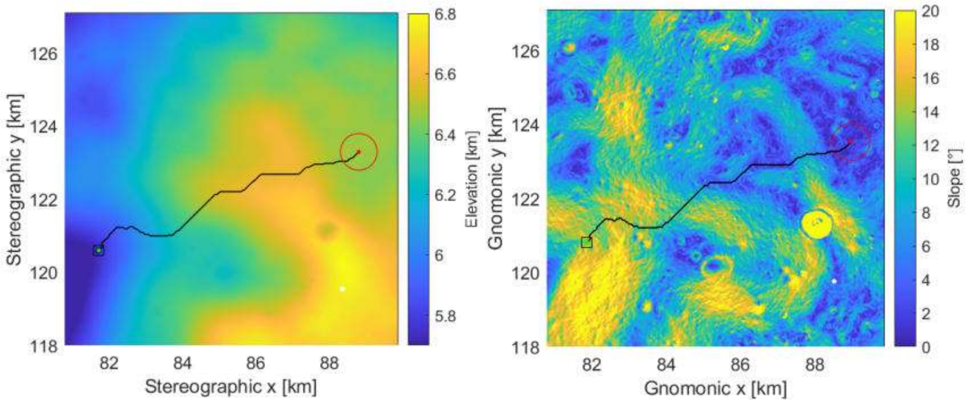


Fig. 8. Traverse from the landing site (red dot) to the WIL (green dot) on the elevation model map (left) and the slope model map (right)

3.2. *Analysis of boundary conditions*

Despite the relatively short traverse from the landing site to the PSR the major challenge was the power requirements of the rover in combination with the very low temperature in the PSR. The rover is based on the LRU design (see [7]) and relies on solar power supported by a battery for shadow areas. Hence, the rover's encounter with cold temperature is to be minimized as well as traverse region in the shadow. This led to the next optimization step assuming a starting time of the rover from April to September 2030.

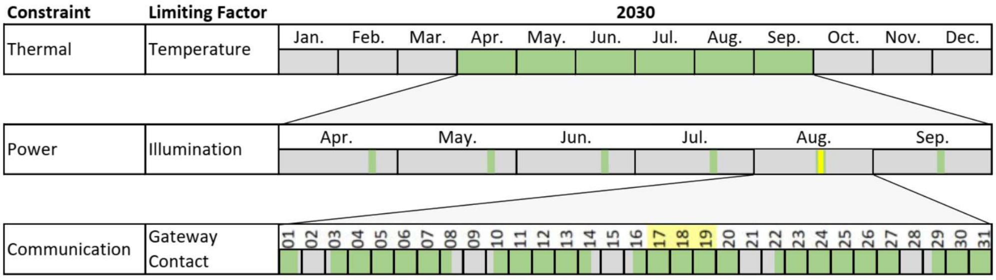
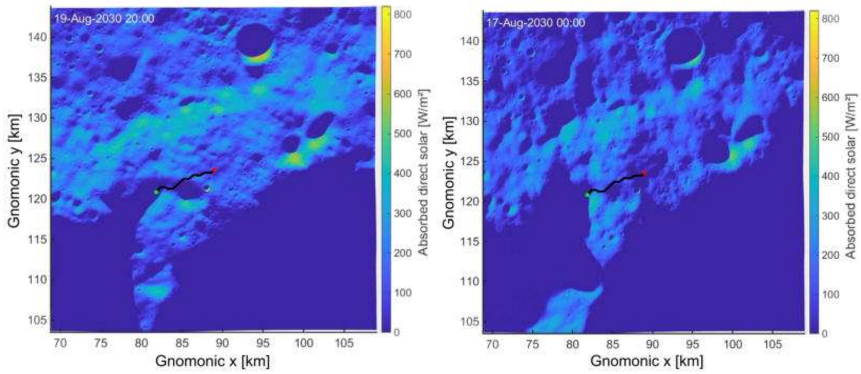


Fig. 9. Summary of the preliminary mission timeframe limitations from thermal, power, and communication constraints for the year 2030

As shown in Fig. 9 several opportunities could be found in the given timeframe with favourable boundary conditions concerning temperature and illumination constraints, about one opportunity per month. In the end the slot from 17 to 19 August 2030 has been chosen, because it offers a good communication conditions according to the currently know ephemerids of the Gateway [9]. Fig. 10 shows the illumination maps of the traverse on 17 and 19 August, which is in the sunlight for a high percentage of the track to avoid power problems of the rover.



(a) 17th August 2030 00:00 UTC. (b) 19th August 2030 20:00 UTC.

Fig. 10. Maps of a section of the Malapert massif, portraying the traverse on the absorbed direct solar load by the surface for different dates.

For the detailed planning approach, the following boundary conditions have been chosen based on the analysis shown above:

- Start the excursion between 17th of August 12:00 UTC and 18th of August 06:00 UTC.
- Enter the PSR no later than 18th of August 17:20 UTC.
- Do not spend more than 7 h continuously in a shadowed region.
- Perform the sampling procedure within 2 h.
- Perform each sample collection within 10 min.

Considering the constraints above the following power input and power consumption for the relevant days are calculated starting on 17 August 2030 at 18:00 shown in Fig. 11. There is a certain flexibility in starting time until 18 August 0:00, i.e. of about 6 hours. If the start of the rover is delayed more, the minimum battery state of charge (SoC) is steadily going to zero and the mission is no longer possible. If a longer delay would occur, the next opportunity as shown in Fig. 9, i.e. one month later, would have to be chosen.

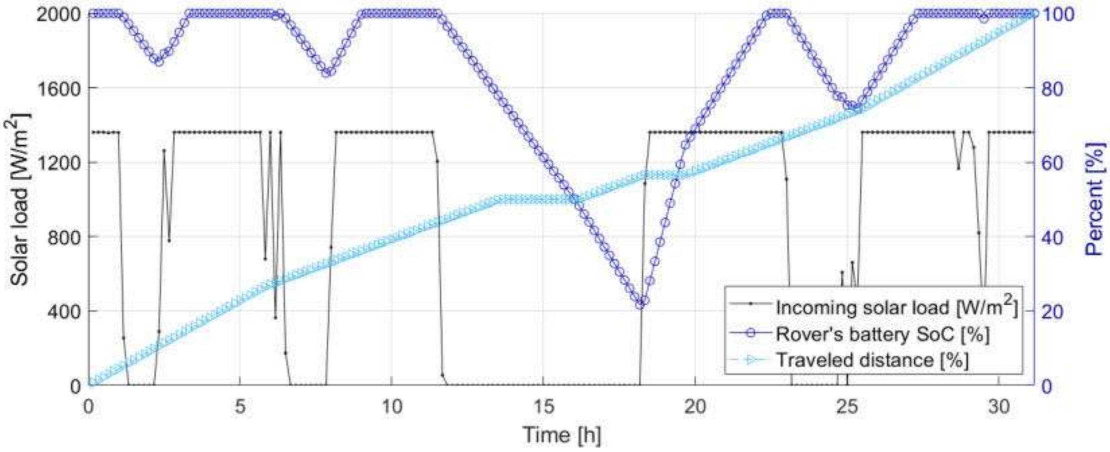


Fig. 11. Graph displaying the incoming solar load [W/m^2], the rover's battery SoC [%] (100% ^= 900 Wh) and the travelled distance [%] (100% ^= 17.4 km) over the mission time [h] for a start on 17 Aug. 2030 at 18:00 UTC

3.3. *Concept of Operations*

Having shown that the mission is feasible from a thermal, power and communication point of view, a detailed timeline is established for the assumed rover excursion to a PSR on the Malapert massive. Fig. 12 gives an overview on the operational timeline with the necessary steps to prepare, execute and follow up of the mission.

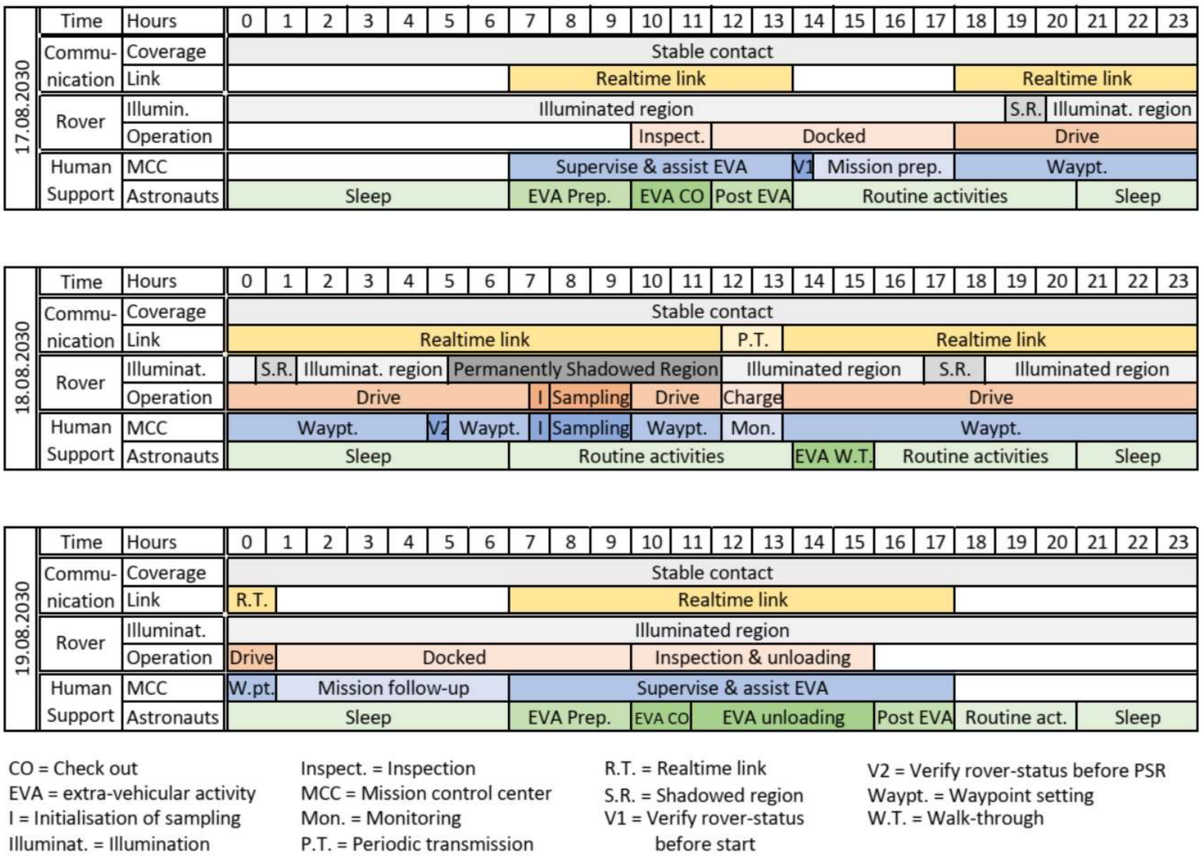


Fig. 12. Operational timeline indicating the sequence and duration of the activities during each mission day

It is assumed that the preparation of the rover is performed by two astronauts for final outfitting and checking the rover. Then the rover makes his way to the permanent shadowed region. Since the rover still requires surveillance and guidance from the ground team in the form of waypoints along the traverse, the ground team has to steer the rover with the help of its downlinked coordinates, orientation, and video transmission. The distance between the waypoints depends on several factors, like the roughness of the terrain, the illumination conditions, and the surface slopes. After reaching the PSR, the WIL area is analysed and the sample collection starts. Depending on the SoC of the battery the sample collection could be shortened to ensure that the rover can reach the next area of sunlight without depleting the battery fully.

The samples are put in a cooled sample container to avoid sublimation of the water ice due to the higher temperature in the sun. When the first illuminated area is reached the rover is configured to charging in hibernation mode to achieve a short loading period due to reduced power consumption. When the rover is reaching the landing zone it will dock to the charging station to ensure cooling of the samples until they can be unloaded. It is foreseen that a first selection of the samples is performed by the astronauts during unloading of the samples and storing them for return to earth. This will include hand sorting of dull samples.

Summarizing the results above, a rover mission to a PSR from a POL seems to be feasible using a current technology rover with solar power supply, only. Nevertheless, the number of sites that could be found are very limited (for the given constraints one site has been found, only) and the boundary conditions, e.g. allowed starting time, offer a small range of flexibility, only. This puts additional constraints on mission planning because a small delay in the preparation of the mission could lead to long delay (a month or more) in the possible starting time of the rover.

4. Results

Two main aspects of the envisaged return to the Moon are analysed in this paper: a Gateway operations scenario and a lunar south pole operations scenario.

The main goal of the Gateway operations scenario was the comparison between a campaign mode approach and a continuous mode approach. The campaign mode offers the advantage of a lower number of flights (crewed and uncrewed flights) and more payload capability but shows the drawbacks of possibly more Gateway reconfiguration and much less crew time on-board Gateway. The continuous Mode offers the advantage of permanently crewed Gateway without reconfiguration and the support of the lunar surface crew by the Gateway crew. In contrary it is necessary to double the number of flight (crewed and uncrewed) to the Moon, a temporary higher load on the ECLSS system and less payload capability. In summary the campaign mode seems to be the best option for one lunar landing per year with a long uncrewed time of the Gateway. If two landings per year should be achieved the continuous mode offers some advantages.

The investigation of the lunar south pole operations scenario showed that mission of a current technology rover using solar power only, seems to be feasible. A landing site in a POL on the Malapert massive has been chosen with a PSR nearby. Detailed analysis showed that a path exists to the PSR which could be handled by the chosen rover. Nevertheless, due to the constraints of the solar power rover and effects of the very low temperature in the PSR the flexibility of this mission is very low concerning location and mission time. Hence, an improved rover with a higher power storage capability or the use of an RTG would offer more adaptability for the mission. Another open topic is the human robotic interaction foreseen in the described scenario. Hence, a first test scenario has been proposed for the LUNA facility [19], which will be built in the course of this year. In a next step it is foreseen to improve and refine the test scenario to be able to perform first test when the facility is available by end of 2023.

5. Outlook

Based on nearly 40 years of experience in human spaceflight as well as 15 years of continuous operations of the Columbus module on the ISS, Col-CC at GSOC will contribute further to the return to the Moon in the course of this decade. The following next steps are planned or have already been initiated:

- Investigations on potential future scenarios like lunar south pole excursion will be continued making use of the new LUNA facility at DLR Cologne. This will allow GSOC to develop and test operations scenarios which could path the way to real time operations support of astronauts on the lunar south pole.
- GSOC has also started an investigation on future operations concepts partly based on AI technologies (see [18]) which are planned to be introduced on the Moon and on future deep space mission. This will allow GSOC to contribute significantly to future missions, e.g. to Mars, which could be the next but one step in human spaceflight.

- ESA has decided to transition the Col-CC into the Human Exploration Control Center (HECC) in Oberpfaffenhofen. It will be responsible on the one hand for Columbus operations until the end of the decade and on the other hand for preparation and operations of the ESA Gateway module IHAB and ERM. This will be done in the course of the Integrated Team which will be extended from ISS to the new missions around and on the Moon like Artemis and Gateway. GSOC has already started operations preparation for the ESA Gateway modules to be ready for launch and operations in the second half of this decade.

DLR/GSOC is looking forward to this exiting decade with many new challenges in course of the next endeavour of human spaceflight – the return to the Moon!

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