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HUMAN LUNAR EXPLORATION: INTERNATIONAL CAMPAIGN DEVELOPMENT

Chris Culbert
NASA Johnson Space Center, USA, christopher.j.culbert@nasa.gov

Yves Gonthier
Canadian Space Agency, Canada, yves.gonthier@asc-csa.gc.ca

Olivier Mongrard
ESA, The Netherlands, olivier.mongrard@esa.int

Naoki Satoh
JAXA, Japan, satoh.naoki1@jaxa.jp

Calvin Seaman
NASA Johnson Space Center, USA, calvin.h.seaman@nasa.gov

Pat Troutman
NASA Langley Research Center, USA, patrick.a.troutman@nasa.gov

ABSTRACT

The International Space Exploration Coordination Group (ISECG) has been working in a coordinated, multi-lateral fashion to develop a point-of-departure architecture for a human campaign to explore the Moon. This architecture builds upon the “Global Exploration Strategy (GES): The Framework for Coordination” document (published in 2007) to identify an approach for implementing a sustained campaign of human exploration of the Moon. The resulting product describes the types of missions required, the sequence to perform them, the type of hardware each mission might deliver to the Moon, and key operational aspects that enable the overall campaign to succeed. The campaign has been evaluated against a list of 15 common goals identified by the ISECG working groups. To perform this activity, the ISECG formed an International Architecture Working Group (IAWG) with the responsibility of coordinating the various elements. The IAWG in turn formed multiple ‘function’ teams, who were given the responsibility of defining capabilities that could be used in human exploration. Function teams included areas such as human habitation, mobility, communications, in-situ resource utilization, servicing, and transportation (to and from the Moon). In addition to the function teams, a campaign integration team was formed to integrate the various products together, develop tools for analysis, and ensure that the resulting series of missions were both technically feasible and capable of meeting specific goals or objectives. This paper describes how this international community, with representation from multiple space agencies, worked together to develop and refine this complex set of material into a cohesive campaign and provides an overview of the resulting human exploration campaign.

INTRODUCTION

The International Space Exploration Coordination Group (ISECG) was established in response to "The Global Exploration Strategy: The Framework for Coordination" developed by fourteen space agencies and released in May 2007. ISECG was created as a voluntary, non-binding international coordination mechanism through which individual agencies may exchange information regarding their interests, plans and activities in space exploration, and to work together on means of strengthening both individual exploration programs as well as the collective effort. Several ISECG participating space agencies participated in the development of the ISECG Reference Architecture to identify an approach for implementing a sustained campaign of human exploration of the Moon. A campaign is defined as “a series of coordinated missions that represent a unique strategy for satisfying a set of goals and objectives over a given timeframe”. It is built upon the assets available within the reference architecture.

This paper describes how multiple space agencies, worked together to develop and refine the ISECG Reference Architecture into a cohesive campaign and provides an overview of the resulting human lunar exploration campaign.

INTERNATIONAL ARCHITECTURE DEVELOPMENT PROCESS

The development of the ISECG Reference Architecture for Human Lunar Exploration marks the first time that a group of space agencies worked closely together to formulate a conceptual definition of a complex human exploration campaign. Over the 18 month study, many lessons have been learned concerning the organization and process required for such a demanding task. The team used these steps to create the human lunar exploration campaign:

1) Review individual agency's lunar exploration objectives and the themes of the Global Exploration Strategy leading to the development of common goals and reference utilization activities;
2) Development of strategic guidance based on strategic and programmatic consideration complementing the common goals;
3) Definition of reference human lunar exploration mission scenarios;
4) Development of the reference campaign for human lunar exploration which describes a sequence of missions over time utilizing the reference mission scenarios as initial building blocks and responding to the strategic guidance;
5) Development and assessment of variations of the developed reference campaign for improving its responsiveness to the strategic guidance and common goals;
6) Conceptual definition of the elements of the architecture required to implement the mission scenarios of the reference campaign;
7) Evaluation of the reference campaign and architecture against the common goals in a pair-wise comparison to alternative lunar exploration campaign strategies.

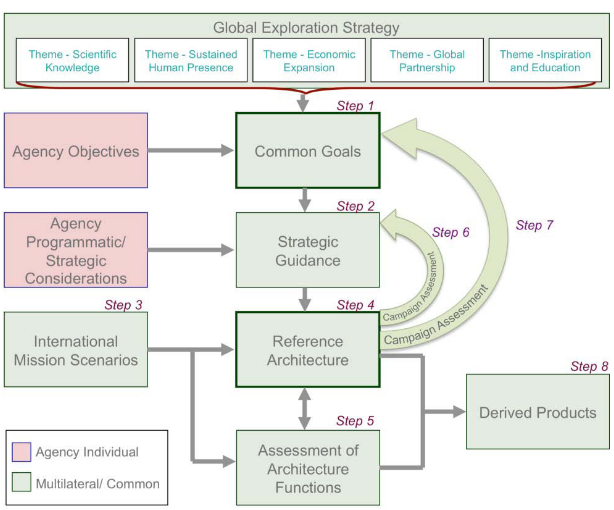


Fig. 1: Reference Architecture Development process

Figure 1 illustrates the development process and the interrelation between the different steps. While these steps are interrelated (e.g. step 7 requires completion of step 4 and 5), many can be performed in parallel (e.g. step 1, 2, 3, 6 have been initiated together) and some require iterations (e.g. step 4 and 5). One important lesson learned is the criticality of agreeing early on definitions used throughout the work. This paper will focus primarily on the activities in steps 4, 5 and 6. More details regarding the activities performed in step 1 can be found in [1], for step 2 and 3 see [2] and [3], and for step 7 see [4].

For the organization of the work 11 international teams have been set-up to support the International Architecture Working Group. The Working Group itself acted mainly as a strategic forum to guide and review the work of the various international teams represented on Figure 2. The 11 teams' roles and responsibilities included:

- The Campaign Integration Team to integrate the campaign and reference architecture, define and assess the overall trade-space, ensure overall programmatic and technical consistency, assure responsiveness of the architecture to the strategic guidance and common goals and identify and assess the critical technologies required to enable the campaign;
- The International Objectives Working Group to review agency objectives, develop common goals and assess the degree of satisfaction with respect to these common goals as well as the utilization opportunities enabled by the reference campaign and architecture;
- Seven Function Teams in the areas of habitation, power, crew and cargo transportation, In-Situ Resource Utilization, communication/navigation, servicing, and surface mobility to analyze key driving requirements for the various architecture functions, identify innovative concepts responding to these requirements and conceptually define the architecture elements. Many of these element concepts are based on individual agency studies performed earlier or in parallel;
- The Interface Standards Working Group to identify international interfaces which would benefit from international standards;
- The Robotic Precursor Phase assessment team to consolidate the strategy for the early robotic missions preparing the human missions of the lunar exploration campaign.

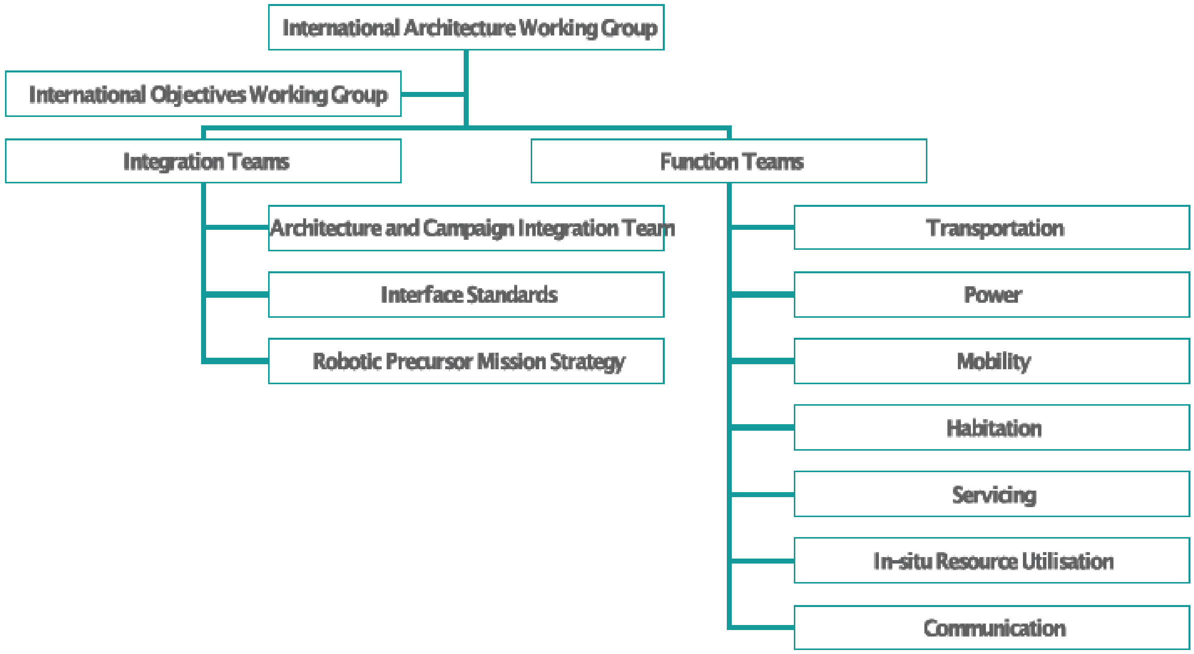


Fig. 2: – IAWG working structure

Not all agencies that have been represented in the IAWG participated in all working groups. Rather agencies decided on their engagement in the process based on the interest and expertise. This enabled all agencies, smaller and larger, to gain full insight and be active and influential in the overall development process.

The teams mainly interacted through teleconferences supported by modern web-based communication tools throughout the study, many of them organizing weekly teleconferences. Workshops enabled the team members to meet face to face and facilitate collaborative decision-making. Throughout the study, each team met at least once face to face.

The function teams played a critical role in developing the technical concepts needed to create a viable architecture, and ensured both technical consistency and feasibility of the architecture. The Campaign Integration Team also ensured at preliminary conceptual level the technical feasibility and closure of the proposed campaigns and provides programmatic data to the steering IAWG to inform their decision-making. In particular, the Campaign Integration Team made sure that logistics to support habitability and crew needs were properly accounted for. A dedicated logistics manifesting tool, the Campaign Manifest Analysis Tool (CMAT) [5] was used to determine whether the produced campaigns are closed from a logistics point of view, i.e., that all logistics required to perform the planned missions (including contingency logistics) are available when needed.

The work has furthermore drawn on the expertise from the ISECG Working Group on Enhancement of Public Engagement for reviewing the common goals and assessing the overall campaign and from the ISS Lessons Learned document published by the Multilateral Coordination Board of the ISS Partners.

ISECG REFERENCE ARCHITECTURE FOR HUMAN LUNAR EXPLORATION

Developed by ISECG participating agencies, the Reference Architecture represents an emerging international consensus on a sustainable and robust approach for lunar exploration. It demonstrates the importance of agencies working together early in program formulation.

The Reference Architecture is neither a lunar base nor a series of Apollo-style (i.e. sortie) missions. It employs a flexible approach to lunar exploration that can accommodate changes in technologies, international priorities and programmatic constraints as necessary. The Reference Architecture reflects expected global budgetary challenges while enabling significant scientific and exploration objectives to be met and reduces risk for future exploration.

Figure 3 illustrates the phased approach, which employs an inventory of international human-rated and robotic assets over time to explore the Moon. Figure 4 illustrates notional locations on the Moon for these phases.

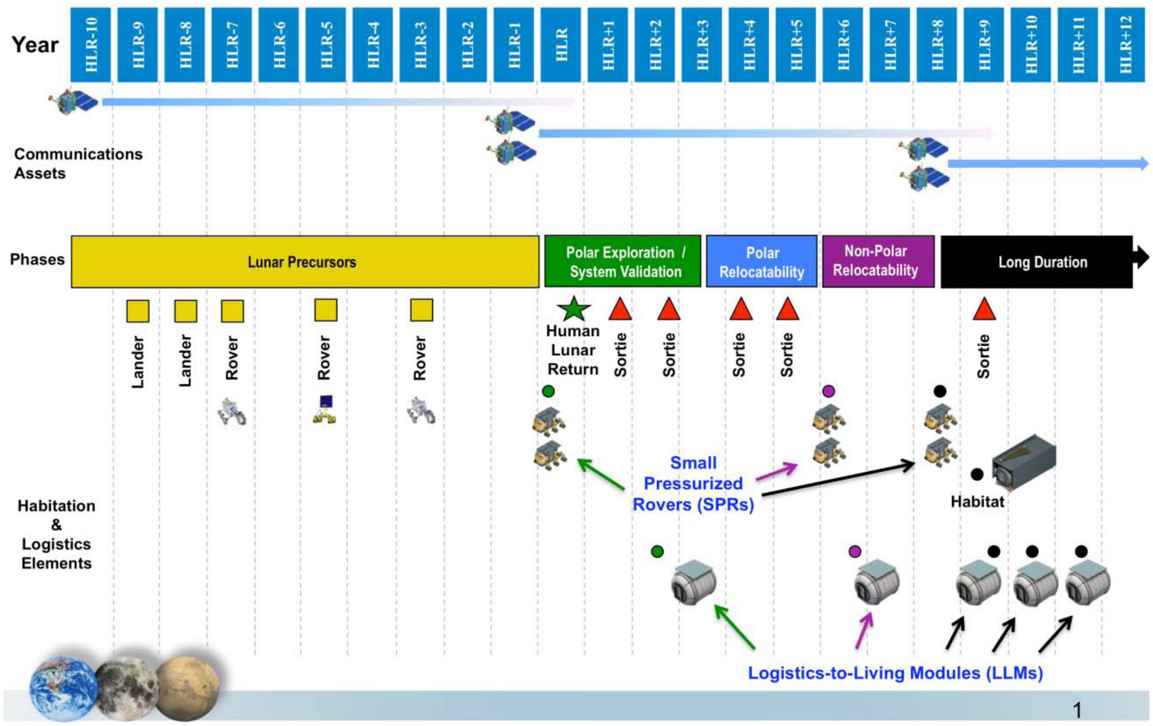


Fig. 3: – Reference Architecture Overview, illustrating phased approach
(The years across the top of the figure indicate years before or after Human Lunar Return)

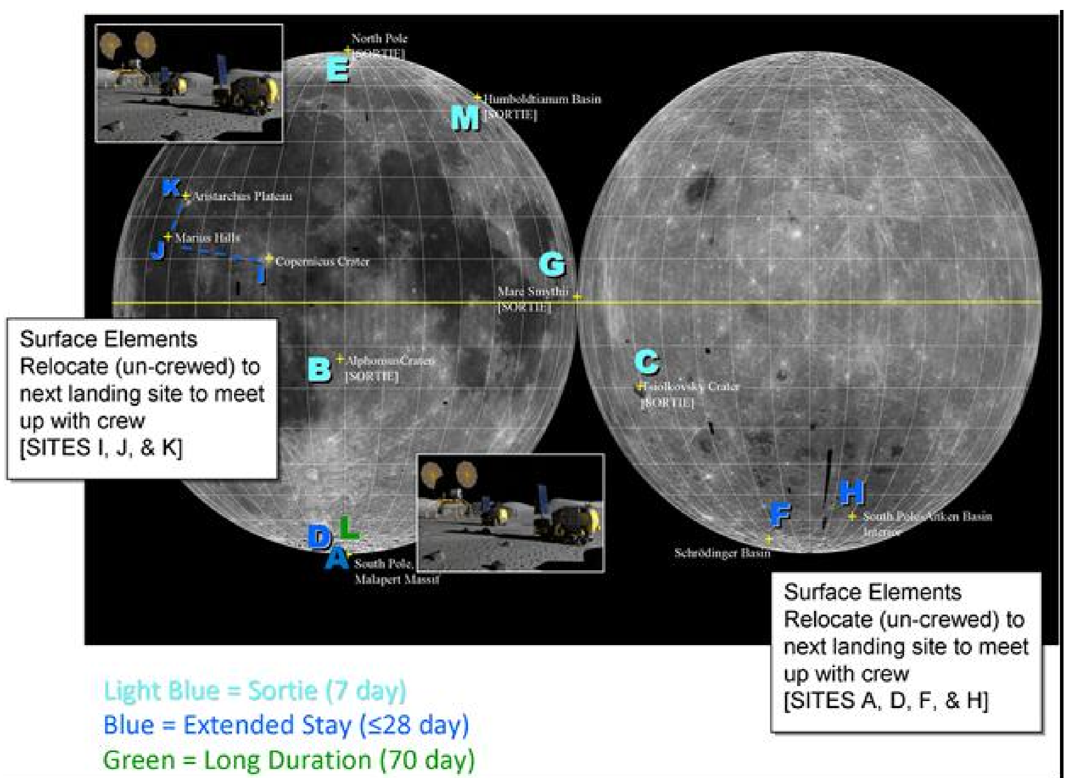


Fig. 4: – Map of the Moon showing notional destinations for the Reference Architecture
(Letters correspond to the locations defined in Figures 6 and 12)

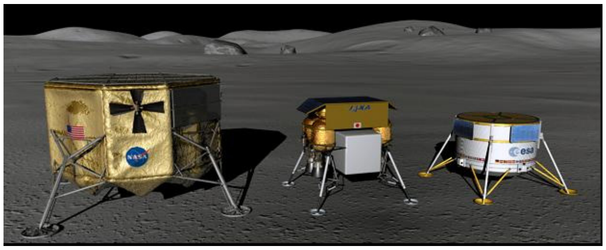


Fig. 5: Reference Architecture cargo delivery elements. (Left) Large cargo lander with payload capacity of up to 14.5t. (Middle and right) Small cargo lander with payload capacity of up to 1t.

Key aspects of the architecture's robustness include opportunities for multiple partnerships and a phased approach that provides space agencies with diverse opportunities for scientific discovery and participation in exploration missions. The Reference Architecture leverages reusable and relocatable surface assets to maximize exploration and participatory exploration opportunities while minimizing the need to deliver cargo to the moon. It makes extensive use of robots working with humans, maximizing utilization of assets deployed across the moon before, during and after each crew visit.

The Reference Architecture relies on NASA's Constellation architecture [6] for crew and large cargo transportation but is robust to variations (increases or decreases) in landed mass. It shows flexibility and redundancy will be improved by also using small cargo landers to deliver scientific payloads and logistics (e.g. laboratory and excavation equipment and crew support items like food, water and clothing). Figure 5 illustrates the transportation systems used to deliver cargo to the lunar surface.

The Reference Architecture is composed of five phases of exploration on the lunar surface. While each phase builds on previous ones, and elements are re-used between phases, each phase involves a different realm of exploration:

• Robotic Precursor Phase: Series of robotic missions to increase knowledge, reduce risk and understand required margins.

• Polar Exploration and System Validation Phase: Validation & verification at pole of Human mobility and power infrastructure.

• Polar Relocation Phase: Uses relocatability to enable extended crew missions to "near polar locations".

• Non-Polar Relocation Phase: Utilizes evolved assets to enable exploration via extended crew missions (at least 14 days) at non-polar regions.

• Long-Duration Phase: Long duration extended stay capability (at least 60 days).

Robotic Precursor Phase

A Human exploration campaign can be performed with a human-robotic partnership, where a robotic phase prior to human missions provides benefits in enhancing the efficiency of the human exploration phases. In the Reference Architecture, robotic precursor operations are included explicitly. Additionally, robotic operations do not stop after human lunar return and play an important role in subsequent phases, both during, and in between, crew surface stay missions.

The primary objectives of the robotic precursor phase include: characterizing the polar and non-polar lunar environment, resource prospecting, materials testing, and demonstrating technology and operations concepts. The precursor missions also provide an opportunity to deploy operational infrastructure, conduct science that may yield particular value prior to the human exploration phases, and offer opportunities for interactive public engagement in real time. This phase will also give existing and emerging space agencies opportunities to consolidate international partnerships. The knowledge gained during the robotic phase will be used to help select future exploration sites, improve safety, and reduce the cost and risk of human exploration missions.

A six-mission robotic precursor phase was developed, beginning 10 years before Human Lunar Return (HLR). The phasing and sequencing of these activities is intended to inform the design and development of architectural elements for subsequent human lunar missions (Figure 3, yellow bar). A detailed description of this precursor phase is given in [6].

The robotic phase will begin with a lunar orbiter mission that deploys a communication relay capability, and builds on mapping and reconnaissance data collected by recent exploration missions, including the Lunar Reconnaissance Orbiter (NASA), Kaguya (JAXA), Chandrayaan (ISRO) and Chang'e 1 (CNSA) spacecraft. Data from these lunar orbital missions will be used to design robotic surface exploration missions to sites of high interest.

The surface missions will include three landers to the South Pole region that perform ground-truth measurements to characterize the local environment, conduct resource prospecting and perform long-duration materials testing. They will also demonstrate a variety of technologies, including advanced systems for automated precision landing, long-duration thermal management and surface mobility. These missions also include high-priority science investigations and transmission of 3-D images and video from the lunar surface.

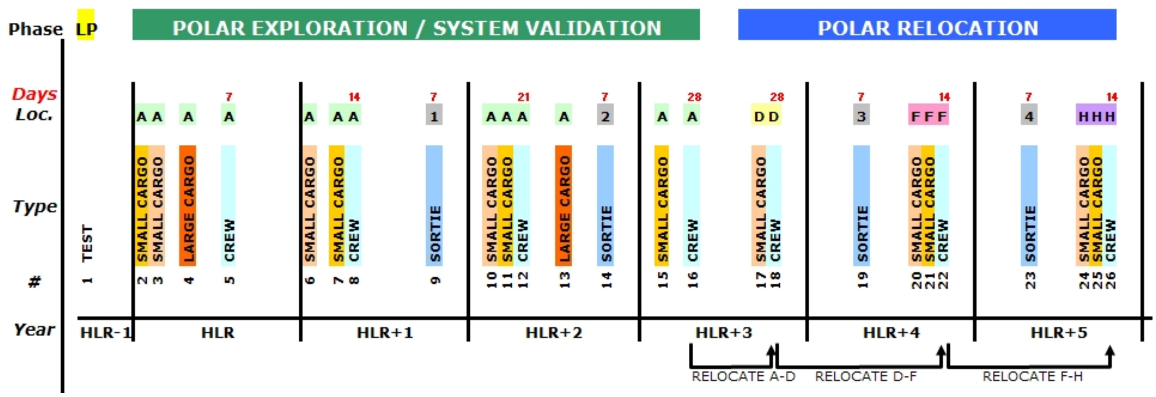


Fig. 6: – Reference Architecture polar phases. Crew surface stay days are mentioned in red. Landing location is denoted with a letter or a number in case of sortie missions. The type and number of flight is also reproduced. Finally years before and after the Human Lunar Return (HLR) are indicated as well.

The next robotic missions will feature mobility and survey functions at nearby sites based on preferred human landing sites planned in subsequent phases. The latter mission will also focus on resource discovery, characterization and extraction, as well as a demonstration of thermal control systems for the extreme non-polar lunar environment.

Polar Exploration and System Validation Phase

The polar exploration and system validation phase leverages all the robotic precursor work to incrementally build up confidence in operations and systems design in preparation for more aggressive lunar exploration. This phase occurs at one of the lunar poles (south pole is used as a reference) due to the favorable solar and thermal conditions, thus not exposing the systems to the harshest operational environment of a full approximately 15 day lunar night until the systems have been deployed and tested. Figure 6 provides an overview of the missions flown during this phase.

A year before any large infrastructure is sent to the moon, several small servicing robots are sent to the surface via small cargo landers that could be provided by international or commercial partners. These systems benefit from the experience gained during the previous robotic missions, but are designed to operate for years as they are part of the human/robotic partnership that will explore the moon hundreds of kilometers from the lunar south pole. This will be the first time ever that multiple robots will be working together in close proximity on another celestial body. The servicing robots will practice servicing operations, scout the region for future crew/cargo landing areas, and deploy landing aides. All robots will send back to Earth a steady stream of engaging and informative data and video, including the descent and touchdown of future crewed/cargo landers (including potential test-flight of the crew vehicles). The use of orbital communication relays is dictated by the need to service the south polar region to support crew and robotic exploration activities for periods longer than 14-days. Two communication relays deployed prior to Human Lunar Return can provide continuous coverage within 500 km of the south pole.

After the site on the moon that will host initial Human Lunar Return (HLR) has been sufficiently investigated by the small servicing robots, the deployment of the large scale exploration infrastructure begins. A year after the initial robotic missions, but before the first crewed mission, two small pressurized rovers and supporting power infrastructure are landed in the polar region by a large cargo lander and self-deploy. The lander contains the two unpressurized rovers, offloading equipment and a large regenerative fuel cell system with solar arrays. It arrives on the surface as directed by the robotically emplaced landing aides. The water produced from the lander fuel cells is pumped directly into the small pressurized rovers, to provide radiation protection or be used as consumables for the crew later on, before the rovers are offloaded (ground supervised) to the lunar surface. The large regenerative fuel cell and its solar array remain on the lander deck as a recharge station for the rovers.

The small pressurized rovers are initially tested, then sent on excursions (in a ground supervised mode) progressively further away from the landing location, beyond the range of the small robots, to identify opportunities and optimal paths that can be used by the humans on the first crewed mission. When the humans, along with any critical spares arrive, the fully checked out rovers are waiting for them. The crew then perform up to a 14 day mission (seven days planned), exploring the near polar region, practicing operations and contingency scenarios for upcoming traverses. Having two small pressurized rovers offers redundancy and rescue capabilities in the event one rover becomes non-operational. The crew leaves the surface at the end of their mission while the robots continue exploring before the next crew arrives, enhanced by portable utility pallets delivered by small international landers.

The next crew arrives eight months later and performs a 14 day mission using the extended range and duration resulting from coupling the small pressurized rovers to the portable utility pallets. A crew does not return to this location for a year as the small pressurized rovers, the servicing robots and the portable utility pallets perform extensive ground supervised exploration. During this period a crewed sortie mission is performed to another location, potentially on the far side, thus having highly capable robots at one location on the moon with a crew visiting another site concurrently. The option exists to send the sortie mission crew to the south pole site if the robots make a significant discovery or require crew intervention sooner than expected. This is part of the reference lunar campaign approach to sustainability – always having options available to reduce risk and to act upon discovery.

Prior to the next crewed mission to the south pole, a small ISRU demonstration plant is delivered and activated by the robotic infrastructure. The main emphasis of incorporating ISRU is to enable long-term exploration sustainability. Because ISRU hardware has never been flown and operated in space, the approach to incorporating ISRU into the lunar architecture is to first demonstrate, then perform pilot operations, before full implementation. Performing early ISRU demonstrations and pilot operations can reduce the risk and cost of long-duration human exploration, and potentially reduce consumable logistics deliveries from Earth in subsequent missions.

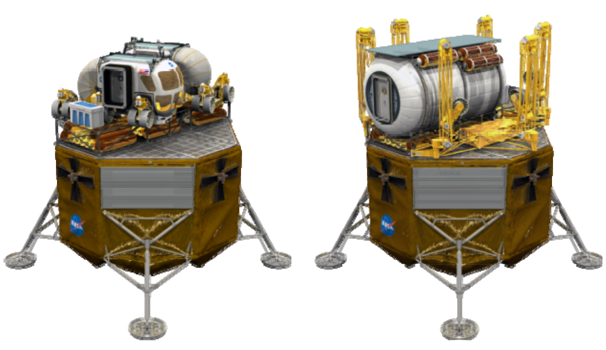


Fig. 7: Largo cargo deliveries packaging for flight 4 (2 SPR and power element) and flight 13 (2 tri-ATLHETE, 1 LLM and a power element)

Almost two years after HLR, a third crewed mission arrives at the pole, with the goal of lengthening the mission duration to 21 days and driving distances on the order of what will be required for exploration beyond the polar region.

Following that crew's departure, another large cargo lander lands near the south pole to deliver the ATHLETE heavy mobility system, another large pallet of regenerative fuel cells, and a logistics-to-living module (LLM) that will enable the crew to stay on the moon for up to 28 days. Figure 7 illustrates the packaging of these payloads on the deck of the large cargo lander. The ATHLETE, under ground supervision and with the help of the lunar robotic fleet, offloads the fuel cells and the LLM after all lander water is scavenged. The new robotic arrivals then join the robotic explorers and begin expanded power and range operations. Another crewed sortie then follows to an alternative lunar location while the newly enhanced robotic fleet explores the south pole. An image describing an International Robotic Exploration Convoy is shown in Figure 8.

An additional small cargo lander brings the logistics to support a 28 day crew mission which performs a dress rehearsal for an expedition in and out of energy friendly regions (i.e. illuminated areas) using all the mobile robotic infrastructure, but never too far from their ascent module. Near the end of their mission, they spend a few days preparing the robotic systems for relocation. The Polar Exploration and System Validation phase is then complete. During this phase, a total of 15 missions have been flown, including four crewed missions, (with durations between seven and 28 days), to the same polar site, and two sortie missions to non-polar sites. Two large cargo landers together with seven small cargo landers have been used to deploy the elements and logistics required to perform these missions gathering 84 days of experience on the surface of the Moon.

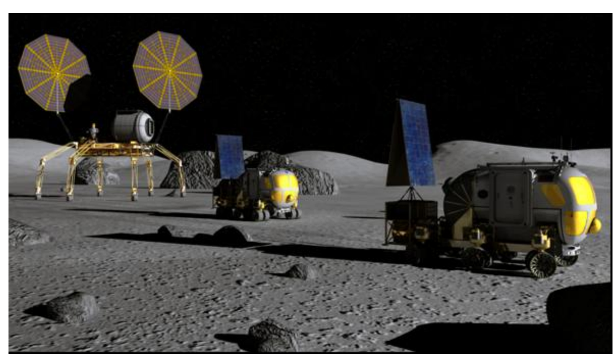


Fig. 8: International Robotic Exploration Convoy

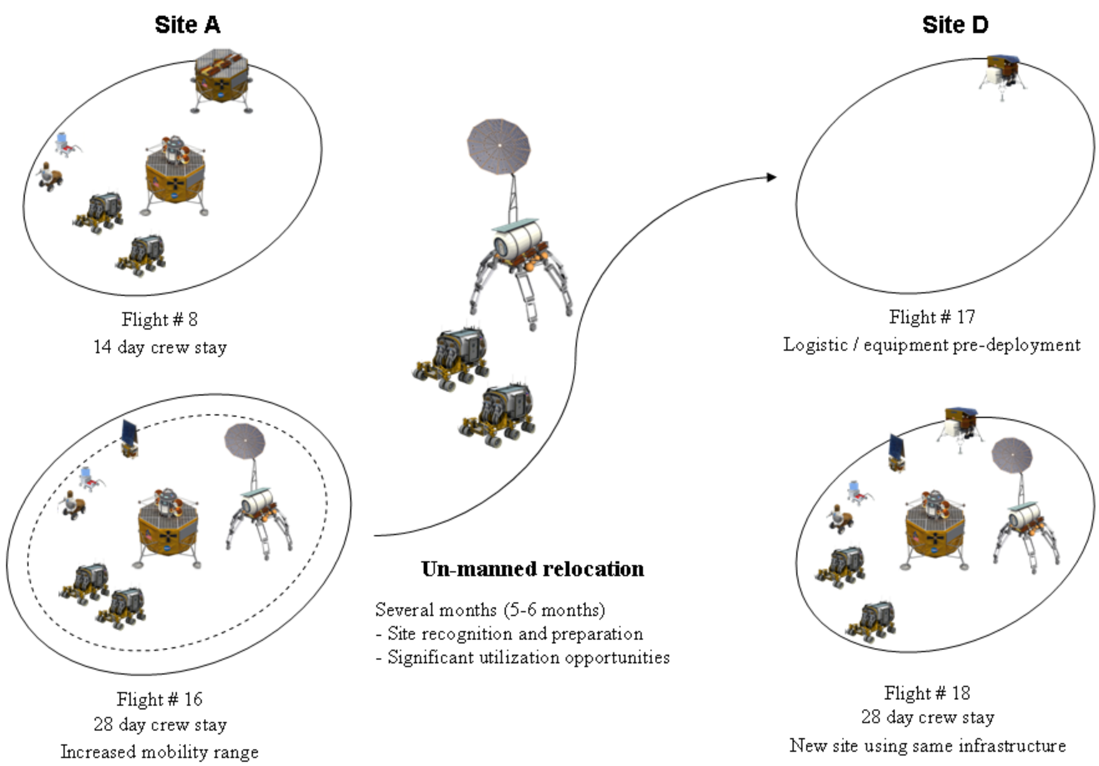


Fig. 9: – Infrastructure build-up at the initial polar site (A) and relocation of assets to site D during the Polar Relocation phase

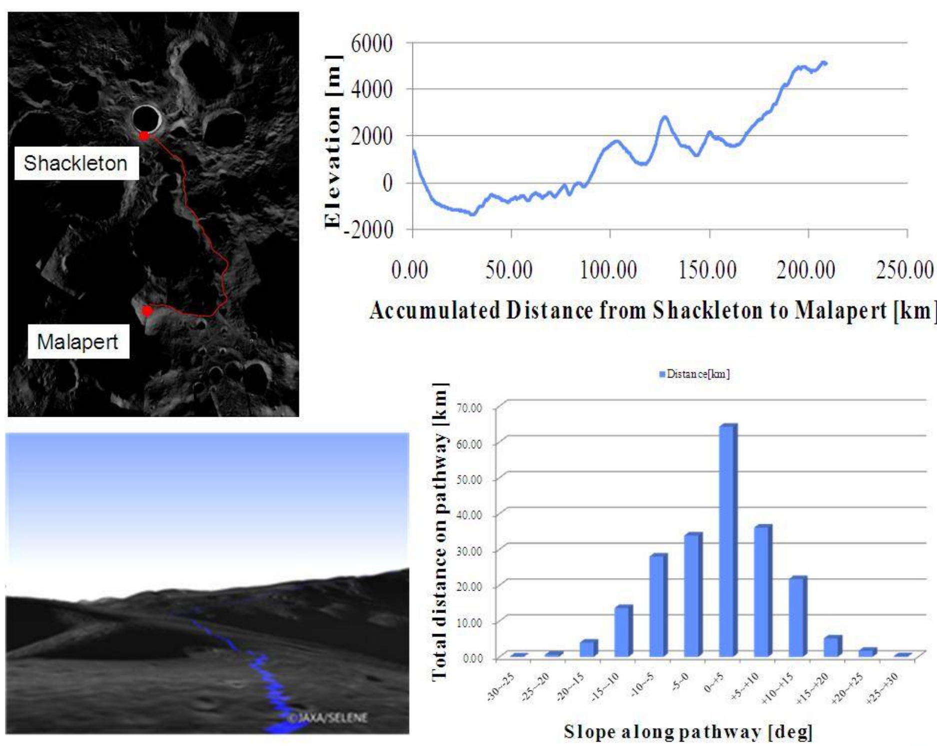


Fig. 10: – Path analysis from Shackleton to Malapert using Kaguya data

Polar Relocation Phase

Almost three years past HLR, the Polar Relocation phase begins. This phase maximizes the utilization of the deployed systems in the absence of the crew while also relocating those systems to meet the crew when it arrives a year or so later at the next exploration site. After each crew departs, the international collection of robots, rovers and systems begin a ground supervised journey to the next site of interest, again, performing science and enabling participatory exploration along the way.

The concept of relocating cargo between human missions allows the utilization of surface assets by multiple crews at different sites as illustrated on Figure 9. This approach also solved the paradox of either having a large mass of equipment in one place versus many short duration sorties to multiple sites. Mobility systems can enable cargo relocation with the rovers driving as unmanned vehicles to new locations and meeting crew that lands at each new site. The Apollo crew could only count on equipment they brought with them. That equipment was disposable, never used again by subsequent crews. Mobility enables a more sustainable program by balancing science objectives requiring visits to many sites and Mars-forward objectives requiring integration of cargo from multiple landers at a common site to enable long stays.

At the beginning of the relocation phase, the robotic systems start their expedition in a ground supervised mode from the initial lunar polar site to the following site such as Malapert. By utilizing the data collected by the terrain camera of JAXA Kaguya (SELENE) orbiter mission, 3-D maps have been analyzed to find a potential pathway from Shackleton crater rim to Malapert as shown in Figure 10. The pathway can be used to estimate the average and maximum slopes along the way which are critical parameters for the design of the mobility elements and also useful to calculate the power requirement during the relocation period. Although the pathway found is not an optimal solution, it is shown that a potential pathway from Shackleton to Malapert exists. The total travel distance along the selected path is 210 km and the maximum slope along the pathway remains within ±30 deg.

When the systems arrive at a new near-polar site for exploration, they begin exploration and reconnaissance operations, months before the crew arrives. The reference campaign always has either robotic science, human exploration or both activities occurring at multiple sites on the Moon, thus enabling a complementary continuous presence.

The crewed lander arrives six months later at the new exploration site with the rovers and other systems ready to greet them. Small cargo landers have also delivered logistics and science equipment to the new site. The crew explores the region for 28 days, informed by the necessary robotic operations that have already occurred at that site. The operations are carefully analyzed and planned such that the energy required to support the elements during eclipse remains smaller than the total available energy.

The crew departs and the robotic fleet begins its journey to the next site of interest (Schrodinger crater as an example). The fleet has a year to relocate and explore, again with an intermediate sortie mission to a non-polar location planned six months after the last crewed polar mission.

As before, the next crewed mission lands at the desired location where the robots are waiting. This time, however, they can only perform a 14 day mission due to the more severe energy constraining environment at the selected site.

The power team analyzed the power balance for each notional mission based on assumptions for daily averages of loads, equipment utilization, and mobility generation for both illuminated and eclipse periods with and/or without crew. Figure 11 shows that for all missions in Polar Exploration and Polar Relocation phases, a power closure was achieved. A more detailed description is provided in [8].

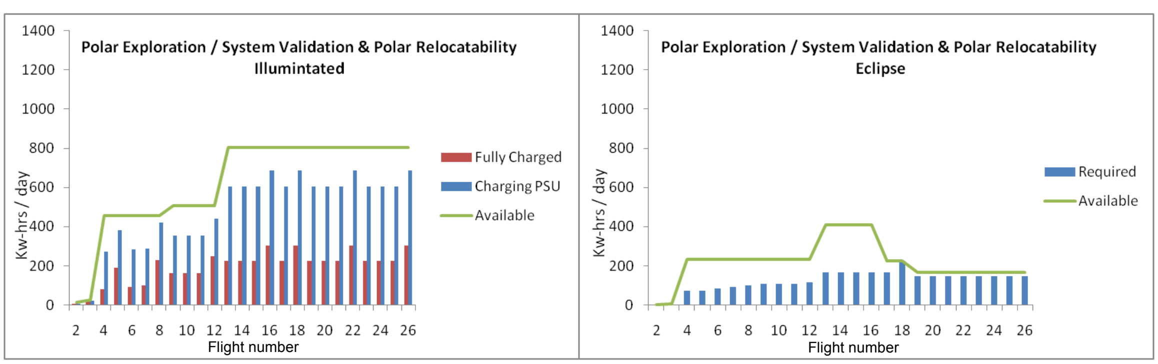


Fig. 11: – Polar Exploration / System Validation & Polar Relocatability Phase Power analysis. Power balance expressed in KW-hrs/day is represented as a function of the Reference campaign flight number.

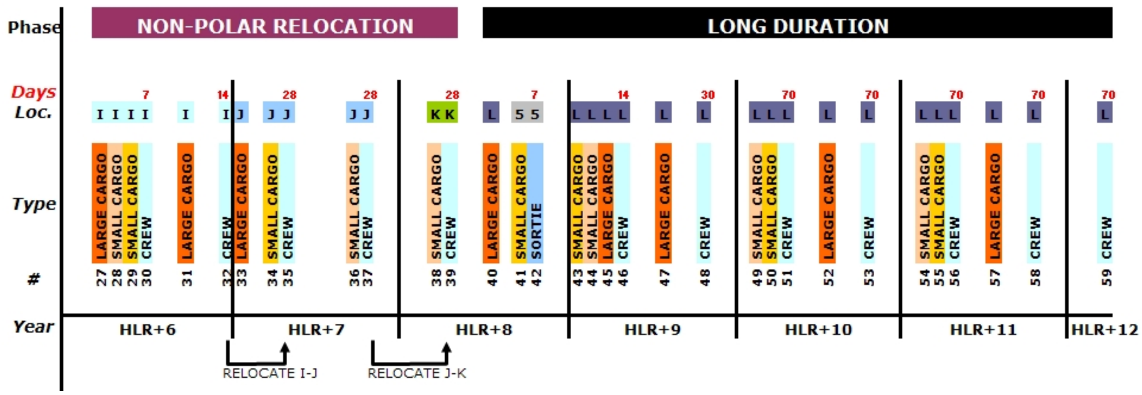


Fig. 12: – Reference Architecture Non Polar and Long Duration Phases. Crew surface stay days are mentioned in red. Landing location is denoted with a letter or a number in case of sortie missions. The type and number of flight is also reproduced. Finally years before and after the Human Lunar Return (HLR) are indicated as well.

After the completion of the mission, the crew returns to Earth while the robots explore on their way back to the south pole, where they can later be used as supplemental spare systems in support of the long duration phase. Six months later another crewed sortie to a non-polar location is planned, and six months after that the crew returns to the pole for 14 days to rendezvous with the surviving robot systems and to prepare them to support a long duration phase.

During the Polar Relocation phase, a total of 10 missions are flown over two and a half years, among which are three crewed missions to different near-polar sites, and two sortie missions to non-polar sites. Only five small cargo landers are used to perform these missions thanks to the ability to relocate the surface assets, enabling 70 crew surface days.

At this point, there are several options in the Reference Architecture. Non-Polar Relocation requires a new/upgraded set of hardware to be launched to another region of the Moon to support multiple 28 day missions. Or short duration crewed sortie missions to specific sites of interest can be performed. Emphasis on long duration human stays may be considered with a series of ~70 day missions to the same site via the addition of several small logistics to living modules delivered on large cargo landers. This would enable a better understanding of the effects of partial gravity and radiation exposure on crew and life support systems. The systems of the ISECG reference lunar architecture can support any combination of the above mission types, independent of the order in which they occur.

Non-Polar Relocation Phase

The Non-Polar Relocation Phase currently follows the Polar Relocation phase in the Reference Architecture campaign. New surface systems, similar to those which were used in the Polar Relocation Phase but upgraded taking into account the initial knowledge gained during the system validation phase, are launched on several large and small cargo missions to a non-polar region of interest on the Moon. Figure 12 provides an overview of the missions flown during this phase. The non-polar regions have more severe thermal and energy environments due to the ~15 days of eclipse and ~15 days sunlight cycle. The reference lunar campaign includes an additional large cargo lander with a big regenerative fuel cell power system and a second ATHLETE system to carry this power system. This power system enables sufficient energy storage for 28 day crewed missions compared to the Polar Relocation phase. This may not be necessary as lessons learned from the first phase of lunar systems coupled with the infusion of updated technologies may be enough to bridge the energy gap. The reference campaign has been structured so that the lessons learned from the first phase of crewed lunar operations can influence the design of the new set of lunar systems used for this phase.

During the non-polar relocation phase, a total of 13 missions are flown over two and a half years. Three large cargo landers and five small cargo landers are used to deploy the elements and logistics required for these missions. A total of 105 crew surface days are enabled at different non-polar sites.

Long Duration Phase

Eight years past human lunar return, surface system technologies, systems and exploration capabilities have been thoroughly exercised. At this time the objectives associated with long duration are addressed. Using the remaining viable infrastructure that exists at the lunar south pole in combination with new mobility, servicing, power and habitation systems delivered on large cargo landers, a series of eight crewed missions spanning over four years are flown. A dedicated habitat and its associated science module are delivered to the surface to allow longer duration stays. Figure 13 illustrates the surface elements involved in the Long duration phase. The mission durations quickly build to 70 days in length at the same polar location, utilizing a nearly closed life support systems and ISRU to reduce logistics requirements. Five 70-day missions are flown during this period in support of understanding the long term (60 days or greater) implications of partial gravity and radiation on a statistically significant number of crew. Five large cargo landers and seven small cargo landers are used to deploy the elements and logistics required for these missions. A total of 394 crew surface days are enabled at the same polar site and seven crew surface days at a non-polar sortie site.

Several options are available after this stage including long duration missions to other destinations, establishment of a lunar outpost, or continued lunar exploration or resource development.

Summary of Reference Architecture campaign

Over the 12 year duration of the reference campaign, 24 crew missions are flown giving 96 astronauts the opportunity to reach the surface of the Moon. A total of 13 different sites are visited and 660 crew days are available to explore the surface, including 242 crew days of pressurized mobility. Five of the crewed missions can remain on the lunar surface for more than 60 days. A total of 10 large cargo landers and 24 small cargo landers are used to support the reference campaign. Table 1 presents a summary of the metrics which illustrate the functional capabilities of the reference campaign for lunar exploration.

Metric	Value
Number of crewed missions	24
Total number of astronauts	96
Cumulative Number of Surface Days	660
Number of Human/Robotic sites visited	13
Number of 60+ day Stays	5
Number of precursor missions	6
Number of Large Cargo missions	10
Number of small cargo missions	24
Cumulative utilization mass (kg)	28 300
Days of pressurized mobility operations	242

Table 1: Reference campaign key Metrics

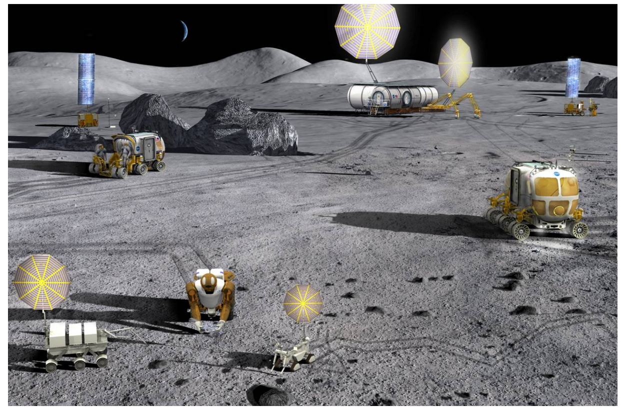


Fig. 13: Long Duration Phase surface elements.

Element Descriptions

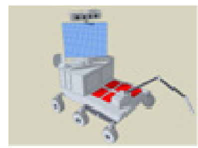
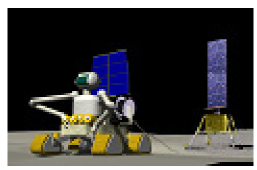
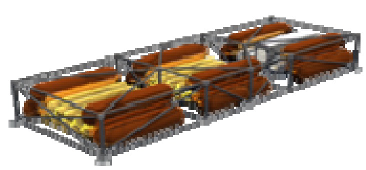
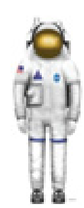
The Reference Architecture requires many systems to be developed and deployed on the Moon, providing numerous opportunities for International space agencies, large and small, to develop dedicated systems in areas of their core interest. There will also be many opportunities for agencies to work together to develop larger systems, allowing effective use of limited resources.

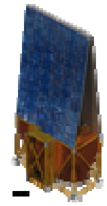
While developing the Reference Architecture, the international team proposed a wide array of elements, support mechanisms and transportation systems at a conceptual level. The selected assets provide a robust set of resources offering long-range mobility and the ability to survive the lunar environment over several lunar day/night cycles. In addition, much of the critical infrastructure may be relocated and reused at different exploration sites as required. Table 2 provides a list of key elements being delivered in the Polar Exploration and System Validation phase.

A SUSTAINABLE ARCHITECTURE BALANCING SCIENCE AND MARS FORWARD OBJECTIVES

Programmatic and Technical Sustainability

Sustainability was a primary focus in developing the Reference Architecture. As a result, the architecture was structured to maximize flexibility and robustness and to allow for changes over time, primarily through the adoption of a phased approach. In addition, the phases are structured and sequenced such that the experience and lessons learned from each can be used to improve subsequent phases. This approach allows participating agencies to meet evolving goals and objectives and to optimize the achievement of exploration goals.

Name/ Functionality	Icon	First delivery	Mass (kg)
Centaur / Robonaut • Versatile robotic astronaut assistant • Rough terrain mobility chassis • Dexterous maintenance or assembly • Inspection • ISRU support • Surface scouting and exploration		HLR	358
RAPIER (robot) • Lightweight rover • Site survey, environment assessment, resources exploitation • Support modular instruments for utilization • Small manipulator		HLR	151
SELENE-X class rover • Tele-operated rover • Offloading of cargo • Site survey, environment assessment, resources exploitation • Deployment, assembly, inspection and maintenance of payloads		HLR	350
Small Pressurized Rover • Modular mobility chassis • Manual, tele-operated and semi-autonomous driving modes • Pressurized cabin with 11 m^3 volume. Carries crew of 2 (4 in contingency). • 2 suit ports for EVA access • Separated docking hatches for emergency and access to other pressurized volumes		HLR	4200
Power and Support Unit • Launch support structure • Provide power and ECLSS consumables • Store up to 950 KW-hrs of energy • Generate up to 14kW of solar power		HLR	2987
EVA Suit • Microgravity EVA capability • 8 hours surface EVA using PLSS		HLR	207

Name/ Functionality	Icon	First delivery	Mass (kg)
Portable Utility Pallet • Power generation (up to 2.2kW) • Energy storage • Water scavenging, storage and transfer • Oxygen storage and transfer		HLR+1	675

Portable Communications Terminal
• Communications connectivity
  o From lunar surface to Earth (Ka and S band)
  o From lunar surface to Lunar orbit
  o Among lunar surface elements
		HLR+1	169

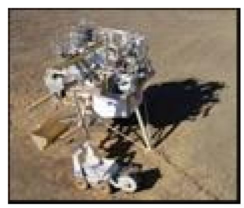
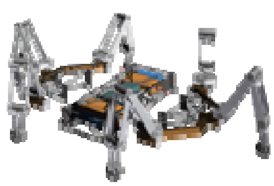
ISRU Demo Plant • Produce oxygen from lunar regolith • Store oxygen in a liquid state		HLR+2	380
Tri-ATHLETE (work in pairs) • Cargo off-loading from landers (up to 14.5t) • Cargo mobility across lunar surface • General purpose manipulator for assembly, maintenance, repair and inspection		HLR+2	1171
Logistics-to-Living Module 2 Segment • Segmented pressurized module • Store up to 4290kg of pressurized logistics • One hatch for crew access		HLR+2	2782

Table 2: Elements of the Reference Lunar Architecture deployed in the System Validation phase.

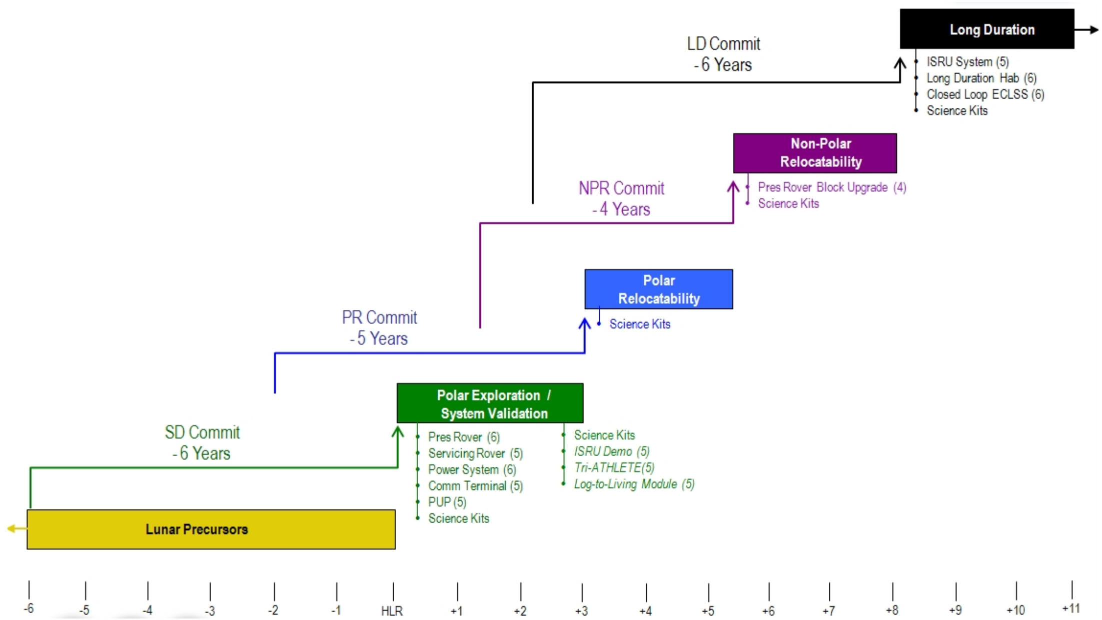


Fig. 14: – Design Commit Points for Reference Architecture Phasing, illustrating flexibility that supports sustainability.

Figure 14 illustrates the structure of the phases and the flexibility and robustness this provides in element design. Because developing and modifying surface elements requires significant detailed design, testing, and production periods, a commitment to the preliminary design of these elements must occur years before they are deployed. The figure illustrates the periods for each phase and also shows the approximate date by which commitments to element design must be made. It shows that the Reference Architecture allows for significant operational experience to be accumulated prior to the commit dates for later phases. This means that elements can be modified and customized in response to actual long-term operational experience and exploration discoveries.

The different phases of the Reference Architecture also allow for large-scale restructuring. The decision points in Figure 14 allow for major adjustments, including but not limited to: switching the order of the phases, introducing new elements and operational concepts, adjusting mission locations, and adding utilization. To validate the flexibility several re-structuring options have been investigated further during the course of the study. Alternative 1 consisted in switching the order of the non-polar relocation phase and the long duration phase such as might be desired due to a change in priorities among goals and objectives or due to discoveries on the surface.

Another alternative considered was to perform a long duration at a non-polar site instead of a polar site. Such a decision might be triggered by a shift in priorities or by a better understanding of the local environment and of the behavior of the systems in such an environment.

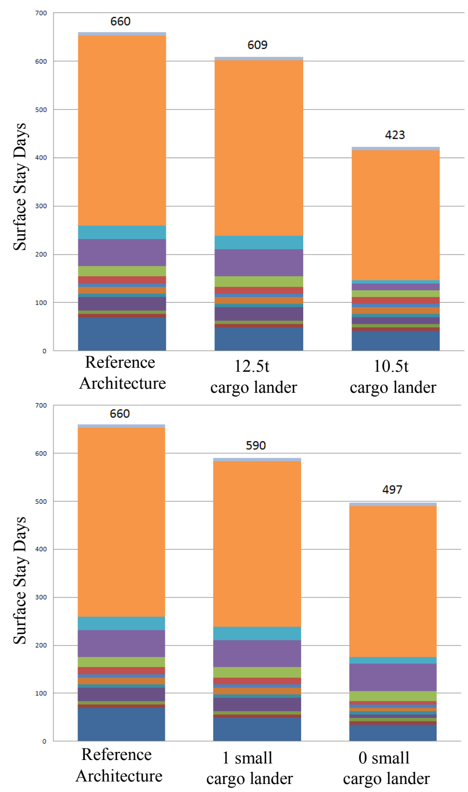


Fig. 15: Comparison of cumulative crew surface stay days for sensitivity to largo cargo capacity (Top) and number of small cargo lander (Bottom).

To verify the robustness of the architecture several sensitivities to key variables were performed. In particular sensitivities to the payload capacity of the large cargo lander and to the number of small cargo landers used per year were computed and are shown on Figure 15.

As the lander capacity decreases, a reduction in the crewed duration occurs as the loss in capacity has to be absorbed by the logistics mass given that the elements and utilization mass remain the same. For a given payload capacity, it is not possible to pack anymore crew consumables, especially pressurized goods, along with the delivered elements on cargo landers and thus the surface days decrease more rapidly.

In a similar way, reducing the number of small cargo landers decreases the cumulative number of crew days by approximately 70 days for only one small cargo lander per year and approximately 160 days for the case without any small cargo lander. Most of these reductions occur within the Polar and Non-Polar Relocation phases.

Balance of Science and Mars-forward objectives

Each phase will involve increased capabilities and an expanded scope of exploration. New elements directly applicable to Mars exploration will be introduced over time. A balance of science and Mars-forward objectives will be achieved by using these new technological capabilities to explore and conduct science on the Moon in a way that mimics modes of exploration that might take place on Mars. The extensive use of mobile assets such as rovers is a key feature that responds to both Mars-forward and science objectives. The reference architecture allows for significant time to be devoted to science and other utilization activities. Some examples of such activities include:

- Fieldwork: Mapping; collecting and analyzing rock and soil samples; measuring the Moon's gravitational, atmospheric and radiation environments; surveying for geological resources and landing sites; education and public outreach events.
- Human health risk reduction: Measuring radiation doses and cardio-vascular function; analyzing blood and urine samples; studying astronaut behavior and performance.
- Flight test and demonstration: Testing navigation and other systems to improve the ability of spacecraft to orbit the Moon; make precise landings on the surface; and avoid landing hazards.

Incorporation of ISS Lessons Learned

Experience from the ISS provided valuable lessons that were incorporated into the Reference Architecture. For example, the Reference Architecture allows for significant delivery capacity and crew time to be devoted to utilization activities during each phase using a progressive build-up of capabilities. This will allow partner agencies to phase assets according to national interests, engage in scientific research, resource extraction, demonstration exercises, public outreach and other utilization activities while the lunar infrastructure is being assembled. On the ISS, science and other utilization activities were significantly delayed by the protracted construction phase and this was a source of frustration to space agencies and the scientific community.

The Reference Architecture incorporates redundant transportation systems, particularly for logistics delivery. The activities planned for the lunar surface require a regular flow of supplies and equipment from Earth and if a single launch system were used, any failures or delays would severely restrict or curtail these activities, limiting the benefits for all partners. The employment of multiple transportation systems to deliver logistics will help ensure that surface operations may continue even if one transportation system fails. This strategy allowed the ISS to survive the loss of Space Shuttle services for more than two years after the loss of Columbia.

CONCLUSION

The ISECG Reference Architecture of lunar exploration establishes a framework that enables significant scientific and exploration risk reduction goals to be addressed by multiple partners through use of a phased approach. The reference architecture's flexible approach to lunar exploration can accommodate changes in technologies, international partner priorities and programmatic constraints as necessary. It maximizes use of mobile and relocatable assets to drive down costs and enhance opportunities for scientific discovery.

The development process among multiple international partners, pioneered for human lunar exploration, can be employed to seek collaboration among space-faring nations interested in future exploration destinations, such as Mars and other bodies in the solar system.

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GLOSSARY

ATHLETE	All-Terrain Hex-Limbed Extra-Terrestrial Explorer
CMAT	Campaign Manifest Analysis Tool
CNSA	China National Space Administration
ESA	European Space Agency
GES	Global Exploration Strategy
HLR	Human Lunar Return
IAWG	International Architecture Working Group
ISECG	International Space Exploration Coordination Group
ISRO	Indian Space Research Organization
JAXA	Japan Aerospace Exploration Agency
ISRU	In-Situ Resource Utilization
LLM	Logistics-to-Living Module
NASA	National Aeronautics and Space Administration
PLSS	Portable Life Support Subsystem
SPR	Small Pressurized Rover

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