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AN INTERNATIONAL STRATEGY FOR HUMAN EXPLORATION OF THE MOON: THE INTERNATIONAL SPACE EXPLORATION COORDINATION GROUP (ISECG) REFERENCE ARCHITECTURE FOR HUMAN LUNAR EXPLORATION

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ABSTRACT

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[1] and released in May 2007. Several ISECG participating space agencies conducted a study of concepts for human exploration of the moon that allow individual and collective goals and objectives to be met. The 18-month study culminated with the development of the ISECG Reference Architecture for Human Lunar Exploration. The ISECG Reference Architecture for Human Lunar Exploration envisions how the space-faring nations of Earth can collaborate in exploring the Moon using the coordinated assets of many space agencies. It marks the first time that a group of space agencies has worked together to define a complex human exploration scenario.

The reference architecture can be used to inform preparatory planning and decision-making within participating agencies. It represents a concrete step towards realizing the vision of the Global Exploration Strategy, which identified the Moon as one of the key destinations for future human space exploration. While pioneered for lunar exploration, this study can serve as a useful model for designing multilateral architectures to explore Mars and other destinations in the solar system.

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[1] In alphabetical order: ASI (Italy), BNSC – now UKSA (United Kingdom), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (European Space Agency), ISRO (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States of America), NSAU (Ukraine), Roscosmos (Russia). "Space Agencies" refers to government organizations responsible for space activities.

The ISECG Reference Architecture for Human Lunar Exploration involves a flexible, phased approach for lunar exploration that is designed to achieve significant exploration goals while recognizing global realities and challenges. It reflects the agency commitments to finding an effective balance between conducting important scientific investigations of and from the moon, as well as demonstrating and mastering the capabilities to send humans farther into the Solar System. In the reference architecture, lunar exploration begins with a robust robotic precursor phase that demonstrates technologies and capabilities considered important for the success of the campaign. Robotic missions will inform the human missions and buy down risks. Human exploration starts with investigation of a polar region while demonstrating and validating the systems needed to take humans on more ambitious lunar exploration excursions. With confidence in the systems and capabilities, human and robotic exploration of the moon will proceed in phases, providing the flexibility to adapt to discoveries or changing programmatic priorities.

The Summary Report of the ISECG Reference Architecture for Human Lunar Exploration can be found on the ISECG website: www.globalspaceexploration.org.

INTRODUCTION

With the release of the Global Exploration Strategy in 2007, and the subsequent agreement to form the International Space Exploration Coordination Group (ISECG), participating agencies recognized the importance of working together to enable a sustainable human space exploration future. In early 2008, many space agencies were active studying lunar exploration scenarios which included human and robotic exploration activities. NASA was beginning Phase A of its Constellation Program lunar transportation system, designed to deliver people and large cargo items to the surface of the moon, and was increasing its focus on the study of lunar surface exploration scenarios. JAXA and ESA were studying methods and scenarios for meeting their lunar exploration objectives. CSA was doing the same with special emphasis on what technologies could be advanced through demonstration in a terrestrial analog setting.

This was the setting in which ISECG invited interested agencies to explore a coordinated approach to human lunar exploration. Interested agencies were invited to participate in a study of lunar exploration objectives and exploration concepts that could meet common agency objectives. It was hoped that this would inform priorities for interfaces that would benefit from standardization, which is an important interest of the ISECG as it works to enable sustainable space exploration. Perhaps more importantly, participating agencies hoped that the study would lead to a common understanding of how humans could best explore the moon, and the partnerships that would enable such an exciting exploration endeavor.

The result of this study is a significant step forward for advancing the Global Exploration Strategy. The ISECG Reference Architecture for Human Lunar Exploration represents an international approach, reflecting the ideas and concepts of engineers and scientists from participating agencies. It also demonstrates the usefulness of ISECG in performing pre-program formulation study work which can subsequently lead to partnerships enabling their realization. By performing this conceptual study work in an open and transparent manner, ISECG is able to inform large and small agencies of the exciting opportunities presented by their participation, as well as enable them to see how their capabilities and long term interests may lead to specific contributions to an international exploration endeavor.

The ISECG Reference Architecture for Human Lunar Exploration is described within this paper, with special emphasis on the important benefits that agencies gained from participating in this study. Lessons learned and derived products will also be described. Additional information on the reference architecture can be found on the ISECG website.

GATHERING BACKGROUND INFORMATION

Participating agencies began by sharing the highlights of conceptual lunar exploration studies they had performed. Agencies shared study results and key findings, illuminating the fact that there were different approaches for human lunar exploration, each delivering different benefits and presenting different challenges. For example, the immediate establishment of a lunar outpost would enable rapid establishment of a lunar infrastructure supporting long term human stays on the moon, up to 180 days, and enabled many lunar exploration objectives to be met. It required a significant early investment and a supply chain from earth to support ongoing activities.

Contrast the outpost approach with an approach largely defined by short duration sortie missions to multiple different locations on the moon. Sortie missions would allow a large number of sites to be studied, but provides a limited opportunity to demonstrate the breadth of surface exploration technologies and capabilities needed for exploration of Mars.

The various approaches were examined and three exploration scenarios were defined: A polar outpost, a sortie mission, and an extended-stay mission. These scenarios were further elaborated in the paper *Advancing the Global Exploration Strategy: Results from the ISECG Lunar Architecture Workshops* (Ref 1). These scenarios served as building blocks which informed the development of the ISECG Reference Architecture for Human Lunar Exploration.

ANALYSIS OF COMMON OBJECTIVES AND STRATEGIC CONSIDERATIONS

Analysis of Lunar Exploration Objectives

While agencies began the ISECG study by sharing the status of their ongoing studies of lunar exploration scenarios and plans, they quickly realized that it was important to assess their individual objectives. Objectives were collected and categorized. Science objectives covered the study of the moon itself and those enabled by using the moon as a platform. Objectives identified the study of the impact of the fractional gravity environment on astronauts and other living things. There were numerous objectives identifying the opportunity provided by the moon to advance and demonstrate technologies and capabilities needed for exploration of Mars (so-called "Mars Forward" objectives). Commercial objectives were also identified, demonstrating the promise of the moon in creating new markets. Lastly, the importance of objectives which ensured that stakeholders such as the general public could be excited by lunar exploration was recognized and important work in this area was begun. The breadth of objectives was impressive and served to highlight many benefits of human lunar exploration which could be embraced by the international community.

ISECG created the International Objectives Working Group, co-chaired by JAXA and NASA, and charged it with analyzing the objectives of individual agencies and looking for commonality which could inform the conceptual architecture study. The IOWG began by inviting ISECG participating agencies to contribute their lunar exploration objectives. The IOWG collected over 600 objectives and analyzed them for commonality. From this analysis, a set of 15 common goals was derived. These goals were used to inform conceptual architecture priorities.

A more detailed description of the IOWG activities and results can be found in the paper *IAC-10.B3.1.11, Developing a Common Set of Human Lunar Exploration Goals and Objectives* (Ref 2).

Strategic Considerations

While the common goals were developed to guide the reference architecture, they are independent of any particular architectural approach or solution. Priority given to one goal over another can significantly change your conceptual approach for exploring the moon. The goals enabled a strategic discussion among participating agencies of where priorities were, and what commonality existed among our individual agency priorities. It also enabled a strategic discussion on other considerations that needed to be agreed because they had a strong impact on the exploration approach. This discussion resulted in the development of strategic guidance to the team exploring architectural approaches. The strategic guidance is listed below.

1. ***Advance the principles of programmatic and technical sustainability and ensure their early incorporation in the architecture***
    a. Apply a phased approach to exploration with interim milestones to accommodate evolution of mission objectives and changes in programmatic priorities
    b. Include a phase that captures robotic missions to the moon in preparation for human lunar surface operations
    c. Consider affordability in laying out campaign approaches
    d. Maximize the synergies between human and robotic activities

2. ***Balance compelling science and Mars Forward objectives, understanding that specific Mars Forward and science priorities will evolve***

3. ***Take due consideration of ISS Lessons Learned including the importance of dissimilar redundancy in critical systems***

THE ISECG REFERENCE ARCHITECTURE FOR HUMAN LUNAR EXPLORATION

The reference architecture can best be defined as a phased, flexible approach to lunar exploration that recognizes that human exploration must significantly advance scientific discovery as well as provide new knowledge that enables humans to go further and do more. The reference architecture can accommodate changes in technologies, international priorities and programmatic constraints as necessary. It enables contributions from many agencies, large and small.

The reference architecture relies on NASA's Constellation architecture for crew and large cargo transportation but the approach is robust to variations (increases or decreases) in landed mass. It employs small cargo landers to deliver scientific payloads and logistics (e.g. laboratory and excavation equipment and crew support items like food, water and clothing.) which significantly enhance the performance and sustainability of the architecture.

Additional information on the ISECG Reference Architecture for Human Lunar Exploration and the process used for its development is contained in *IAC-10-A3.2A, Human Lunar Exploration: International Campaign Development* (Ref 3).

A Phased Approach

The Robotic Precursor Phase- Robotic precursor operations are important to the reference architecture. This phase plays a key role in preparing for human lunar exploration and therefore is considered a key component of the human lunar exploration architecture. The importance of considering the benefits provided by a robotic precursor phase as an integral part of the human exploration campaign is a key lesson learned of this study activity.

The primary objectives of the robotic precursor phase are characterizing the polar and non-polar lunar environment, resource prospecting, materials testing, and demonstrating technology and operations concepts. The knowledge gained will be used to help select future exploration sites, improve safety and reduce the cost and risk of human exploration missions. The phase will also enable public interest and involvement in

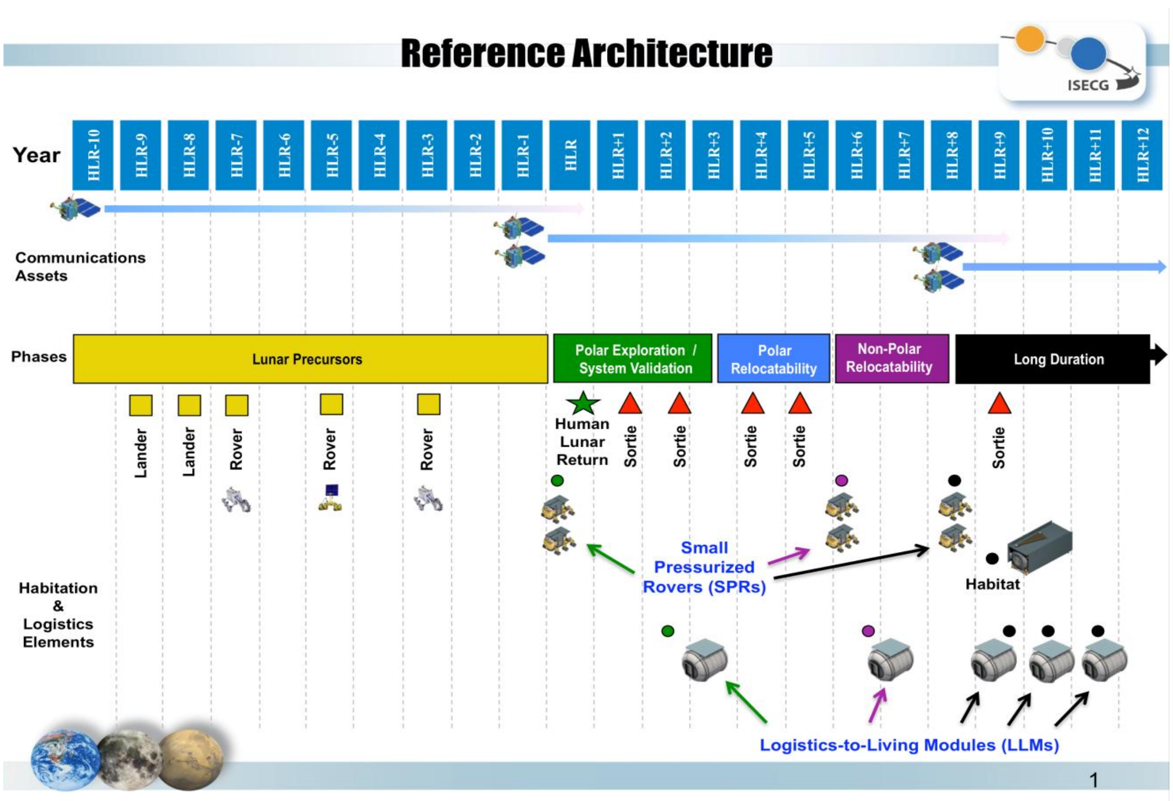

Figure 1: The ISECG Reference Architecture for Human Lunar Exploration

the emerging lunar exploration campaign. Much information has been gained by robotic missions to the moon in recent years. Missions such as Lunar Reconnaissance Orbiter (NASA), Kaguya (JAXA), Chandrayaan (ISRO) and Chang'e 1 (CNSA) spacecraft have provided game-changing information and rationale which guides lunar exploration. The robotic precursor phase is intended to build on this to inform the specific plans for human lunar exploration.

The robotic precursor missions, shown in Figure 1 (yellow bar), are not intended to be a prescriptive combination of instruments and demonstrations. They are intended to reflect a representative grouping of the capabilities deemed important and interesting by the study team.

Additional information on the robotic precursor phase is contained in *IAC-10-B3.6-A5.3.10, Robotic Pre-Cursor Missions: Enhancing Human Exploration* (Ref 4).

<u>The Polar Exploration and System Validation Phase-</u> This phase (Figure 1, green bar) will take place at one of the lunar poles due to favourable solar and thermal conditions in these regions and their inherent scientific value. Once the systems have been successfully deployed and tested at the pole (including surviving full ~15-day lunar eclipse periods), full exploration around the pole is enabled.

The phase begins by sending small cargo landers, ferrying several small servicing robots and a pilot In-Situ Resource Utilization (ISRU) plant to the surface. These systems will build on the experience gained during the precursor technology demonstration missions. They will be key parts of the human/robotic team that will explore the Moon, and their arrival before the first human explorers will allow a maximum amount of productivity when the humans arrive.

The servicing robots will support the deployment and operation of the ISRU plant, practice maintenance operations, scout the region for future crew and cargo landing areas, and deploy landing aides. All robots will relay data and video, including the descent and touchdown of future crew and cargo landers, back to engineers and scientists on the Earth.

When the human landing site has been identified and investigated by the small servicing robots, the deployment of the large-scale exploration infrastructure will begin in preparation for human missions. Approximately one year after the initial robotic missions, but before the first human mission, a large cargo lander will arrive on the surface, directed by the landing aides placed by the robots. It will contain two pressurized rovers, offloading equipment and a large regenerable fuel cell system with solar arrays.

The first exploration crew will arrive and begin their surface exploration missions, lasting up to 28 days. These missions will fully explore the polar and near-polar region, gaining confidence in the systems which will then be capable of branching out further and longer.

<u>The Polar Relocation Phase-</u> During the Polar Relocation phase (Figure 1, blue bar), the team of robots, rovers and surface systems deployed to the lunar polar region will be relocated to the next site of interest for human exploration. Concepts for these elements can be seen in Figure 2. On their journey, they can conduct scientific observations and provide opportunities for interactive engagement with the public. The first exploration site selected is Malapert Plateau. This site was selected based on its interest to the science community, but it should be considered a planning reference location which could be replaced by another near-polar location of interest.

As before, the crew will arrive in their lander and explore the region for up to 28 days. The advanced scouting done by the robots will increase the efficiency and productivity of the human crew's exploration activities. This relocation cycle can be repeated, based on emerging priorities, until the technological systems reach the end of their useful lives.

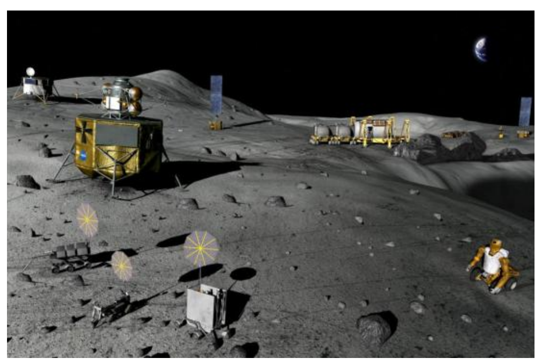

Figure 2: Elements of the Polar Relocation Phase

<u>The Non-Polar Relocation Phase-</u> This phase (Figure 1, purple bar) provides the opportunity to deliver an upgraded and completely new suite of exploration systems and demonstrate their

capability while exploring a non-polar location. By building into the plan the opportunity and budgets for upgrading and enhancing the hardware and systems necessary to explore, support the crew, and perform scientific exploration, participating agencies can take another step towards ensuing their readiness and reliability to support more challenging missions exploring the surface of Mars.

The reference architecture selected Aristarchus Crater as a promising location for in-depth exploration. By committing to deliver the hardware necessary to support the crew for extended surface operations (beyond those provided by a Sortie mission), agencies can ensure a comprehensive exploration of the selected regions, including even the possible deployment of scientific infrastructure that could benefit from longer term human tending.

Long Duration Phase- The final phase of the reference architecture (Figure 1, black bar) calls for the delivery of additional infrastructure to support longer term human stays. The reference architecture envisions stays of approximately 70 days, but longer duration stays are certainly possible. Such a phase will enable the longer duration human missions considered important to provide the opportunity to better understand the effects of partial gravity and surface radiation exposure management on crew and life support systems.

In this phase, logistics-to-living modules or larger habitats are delivered on large cargo landers. As this phase comes later in the reference architecture, we have had the opportunity to gain experience with long duration life support systems and ensure they can operate without the supply chain from earth currently required to support the International Space Station. This is a critical element of the strategy to prepare for human missions to Mars, where equipment must be reliable and an expensive supply chain from earth is not even possible.

In summary, the reference architecture enables exploring a large portion of the lunar surface (Figure 3) and it enables demonstration of the key capabilities considered necessary for surface exploration of Mars. With the close proximity of the Moon, it provides an excellent opportunity to advance the capabilities needed for sustainable space exploration, while enabling expansion and strengthening of the international partnerships considered necessary to explore the exciting and challenging destinations beyond.

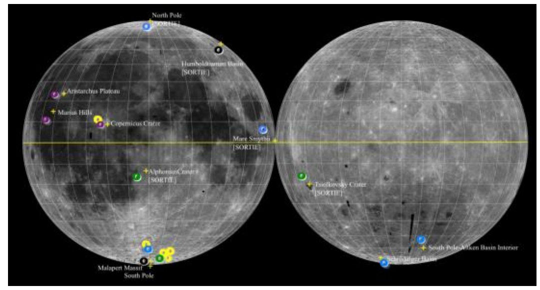

Figure 3: Lunar exploration notional locations in the reference architecture, colors correspond to the phases in Figure 1

USING THE REFERENCE ARCHITECTURE TO INFORM NEAR-TERM AGENCY DECISION MAKING

This section highlights several products of particular interest in the pre-program formulation phase. Participating agencies see the value of a reference architecture in informing individual agency decision making and enabling coordination of their activities in these areas to prepare for human space exploration.

1. ***Critical Technologies**:* The reference architecture has identified key technology challenges associated with the lunar mission as currently defined. The success of meeting these challenges requires key enabling technologies. In the context of the reference architecture, "critical" technologies are those required to implement the defined mission architecture and operational concepts.

2. ***Interface Standards*****:** Interface standards were recognized early on as a critical matter for the international community to consider in developing the reference architecture. Agreeing on an international standard interface is a resource intensive effort, so participating agencies look to the reference architecture to inform priorities for such discussions.

3. ***Innovative Approaches and Concepts***: In the course of developing the reference architecture, some new technical approaches were identified. Most have not been completely defined, but they represent areas where collaboration has already spawned new ideas and improved the technical foundation of the architecture. Examples include logistic-to-living concept, waste and trash management approaches, and integrated ISRU.

The development of the reference architecture was an opportunity for the participating agencies to adjust some of their programs. For example, the CSA used its on-going preparatory exploration program named Exploration Core to develop its contributions to the architecture. NASA and CSA used the reference architecture to help in shaping the terrestrial analogue activities and deployments such as the ISRU validation done in Hawaii in January 2010.

THE SIGNIFICANCE OF A REFERENCE ARCHITECTURE IN INFORMING FUTURE PARTNERSHIPS

The development of international reference architectures for exploration is an instrumental element for facilitating coordination of international efforts and the formulation of future partnerships. ISECG has been created as a forum for advancing international work on architectures with this in mind. International coordination at an early stage of architecture formulation is considered important for exploring concepts that reflect common goals, optimise the opportunities to achieve the objectives of the individual partner agencies and maximise opportunities for broad international engagement and cooperation.

This reference architecture can be the foundation for important multilateral work leading to the setting-up of future partnerships enabling the implementation of the Global Exploration Strategy. If agencies decide to pursue lunar exploration collectively, forward work may include:

1. ***Advancing the Formulation of Reference Architecture***: The formulation of the reference architecture is currently not mature enough to begin phase A program definition activities. Agencies committed to engaging in collaborative lunar exploration would perform activities such as:

    - Evolve Common Goals and Objectives: Participating agencies will require a deeper understanding of, and ultimately agreement upon, common objectives in all of the areas addressed by the common goals. An understanding of the degree to which objectives can be met, based on measurable criteria of objective satisfaction, will be needed to support this dialogue.
    - Define the International Transportation System: In the reference architecture, the capabilities of the transportation system were treated as an invariable constant since NASA had established Constellation transportation system. Additional work will be required to study alternative transportation options.

2. ***Exploring Partnership Interests***: Limited dialogue on the roles and interests of participating agencies in contributing to an international lunar exploration undertaking has been performed. Such dialogue requires matured exploration policies and plans of ISECG participating agencies. The ISECG Reference Architecture and its future evolutions provide clearly a structuring framework for such a dialogue.

3. ***Developing the Cooperation Framework***: The development of the cooperation framework for lunar exploration (and for exploration overall) will depend on the nature of the exploration architecture that is ultimately adopted by the international community. The cooperation framework and associated management structure must ensure that lunar missions will be conducted safely, efficiently and effectively to achieve defined goals.

4. ***Defining Near-term Cooperation Opportunities:*** By identifying enabling research and technology development and critical international interfaces, the reference architecture may help to foster early and focussed collaborative activities among the partners. Demonstration of critical technologies onboard ISS and Earth analogue missions represent two important methods partners can use to advance and demonstrate the capabilities needed for lunar exploration.

5. ***Defining Opportunities for Private Sector Engagement***: The reference architecture helps to identify opportunities for private sector engagement and investment by giving an idea of the market potential in developing products and services for lunar exploration. Areas that could benefit from private sector investments are those with recurrent production and service demands, such as communication/navigation, cargo transportation and logistical services. An enabling international legal and policy

framework is needed to encourage private sector engagement and ensure a market size above the critical level.

6. ***Engaging Stakeholder Communities***: The reference architecture represents an excellent tool to engage stakeholder communities: it outlines utilization opportunities for the scientific communities, tells an inspiring story to the interested public, engages the private sector with technical challenges and possibly new markets, and can engage academics and educational institutions in related enabling research. Tailored messages and communications must be developed for different audiences.

The benefit of having a reference is that it provides a way to measure progress and improvement. The reference architecture itself can certainly be improved. One good way to do this in the near-term while engaging the broader stakeholder community would be to issue an open call to international academics, educational institutions and the private sector to contribute innovative ideas.

CONCLUSIONS

The ISECG Reference Architecture for Human Lunar Exploration represents an international approach to human lunar exploration. In working together early in the conceptual formulation of a major human spaceflight exploration endeavor, agencies have the opportunity to influence, input, understand and define a common approach to meeting their objectives. It demonstrates the usefulness of ISECG in performing pre-program formulation study work and demonstrates the benefits of performing this work multilaterally to inform agency near term decision making which may align the exploration plans of participating agencies.

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William Cirillo/NASA
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