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INTERNATIONAL SPACE STATION (ISS) LESSONS LEARNED AND THEIR INFLUENCE ON PREPARATIONS FOR HUMAN EXPLORATION BEYOND LOW EARTH ORBIT

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ABSTRACT

As the end of the International Space Station (ISS) assembly phase approached, the ISS Multilateral Control Board took the opportunity to reflect on lessons learned by the partnership during the design, development and initial stages of operation of the ISS. This work culminated in July 2009 with the release of a document titled *International Space Station Lessons Learned as Applied to Exploration*. The document contains a rich collection of technical and programmatic lessons learned spread across 7 major categories. The categories Mission Objectives, Architecture, Partnership Structure and Coordination, External Communications, Operations, Utilization and Commercial Involvement provide many useful insights for agencies planning partnerships to undertake exploration missions beyond low Earth orbit. It highlights the importance of developing a long-term shared vision through the early identification of common goals and objectives, common messaging on the importance of the partnership to stakeholders, and the importance of finding roles for each partner that are consistent with capabilities and long term interests. It also identifies many strategies for ensuring an exploration program is robust in a changing political and technical risk environment. The ISS Program thrives today as an example for human exploration programs because of the strategies employed over time to build a partnership which is resilient in a changing environment.

With these documented lessons learned in hand, and the experiences of people who have spent many years working on ISS program, the International Space Exploration Coordination Group (ISECG) has ensured that these valuable lessons are reflected in the work to build a coordinated international strategy for future human exploration of places like the moon, asteroids and Mars.

The ISECG was established in response to “*The Global Exploration Strategy: The Framework for Coordination*” developed by fourteen space agencies¹. The ISECG enables interested agencies to develop the products considered important to inform their individual decision making, enabling decisions to be made in a coordinated manner. In developing the *ISECG Reference Architecture for Human Lunar Exploration* and the *Global Exploration Roadmap*² participating agencies have reflected on the appropriate lessons from ISS to enable a more robust future exploration scenario. This paper will review the ISS Lessons Learned and share insights into how they have specifically influenced the early planning for human exploration beyond low earth orbit. It will also provide additional thoughts on the importance of

¹ In alphabetical order: ASI (Italy), 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), UKSA (United Kingdom),.

“Space Agencies” refers to government organizations responsible for space activities.

² To be released in Sept 2011.

building on the ISS and its legacy for enabling the challenging international exploration missions of the future.

For more information on the ISECG please consult the ISECG website at www.globalspaceexploration.org or contact the ISECG Secretariat at: isecg@esa.int.

INTRODUCTION

Over the years, many efforts at documenting lessons learned have been undertaken by government, industry and academic groups. The discipline of knowledge capture has grown and become very important in sustaining many endeavours. As the end of the International Space Station (ISS) assembly phase approached, the ISS Multilateral Control Board took the opportunity to reflect on lessons learned by the partnership during the design, development and initial stages of operation of the ISS. This occurred at a time when several agencies were formulating exploration programs or performing architecture studies related to space exploration. The ISS work culminated in July 2009 with the release of a document titled *International Space Station Lessons Learned as Applied to Exploration*. This document has proved very effective in highlighting many key topics which have contributed to the programmatic and technical robustness of the ISS Program over the last 3 decades.

In advancing the global exploration effort, the purpose of the International Space Exploration Coordination Group (ISECG) is to provide a forum where interested agencies can share their objectives and plans, and explore concepts that reflect synergies. They can develop pre-program formulation products which enable individual agencies to take concrete steps towards a role for themselves in a future exploration partnership. With this mandate, the lessons learned in design and operations of the ISS are important considerations.

The ISS Lessons Learned document has proven to be very effective in enabling ISECG to focus on important considerations which are relevant to its work. The ISS document is written at a high level, thoughtfully capturing important lessons and the essential elements of each lesson. For this reason, it becomes an effective reference and proves time and again to facilitate community convergence on important considerations affecting ISECG work. Not all lessons learned products enjoy this success. This paper will provide an overview of how the lessons learned have been considered and incorporated by the ISECG teams developing exploration planning products.

OVERVIEW OF ISS LESSONS LEARNED AS APPLIED TO EXPLORATION

In 2008 and nearing the completion of on-orbit assembly, the ISS Program committed to capturing technical and programmatic lessons learned throughout its life-cycle. This decision was made in light of emerging planning by ISS partner agencies for exploration beyond low Earth orbit, and the desire to ensure that the lessons learned of the ISS team were understood and considered.

The ISS Multilateral Control Board, the highest management board involved in the execution of ISS Program activities, invited all agencies to submit their recommendations for inclusion in this activity. The inputs were reviewed by a NASA team, categorized for ease of understanding, and integrated into a draft document. Several iterations on the document were developed and reviewed by the members of the Multilateral Control Board. After discussion of several points, the board reached consensus to publish the document. This was done during the summer of 2009.

The result is a document which contains a rich collection of technical and programmatic lessons learned spread across 7 major categories. The categories Mission Objectives, Architecture, Partnership Structure and Coordination, External Communications, Operations, Utilization and Commercial Involvement provide many useful insights for agencies planning partnerships to undertake exploration missions beyond low earth orbit. It highlights the importance of developing a long-term shared vision through the early identification of common goals and objectives, common messaging on the importance of the partnership to stakeholders, and the importance of finding roles for each partner that are consistent with capabilities and long term interests. It also identifies many strategies for ensuring an exploration program is robust in a changing political and technical risk environment. A view of the completed ISS is shown in figure 1.

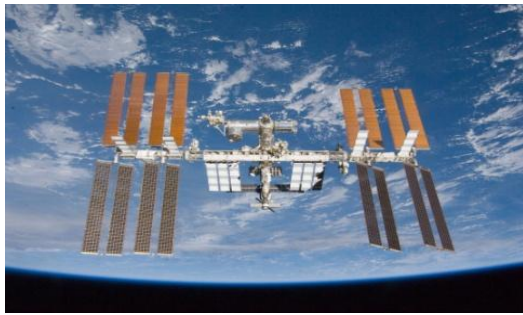


Figure 1: The International Space Station as seen from the U.S. Space Shuttle

INFLUENCE OF ISS LESSONS LEARNED ON THE ISECG REFERENCE LUNAR ARCHITECTURE

The ISS Lessons Learned document was heavily considered by the ISECG International Architectures Working Group (IAWG) during development of the ISECG Reference Architecture for Human Lunar Exploration. Several ISS participating agencies were active within the IAWG and able to bring ISS experience to the early ISECG dialogue. In addition, the ISS document was reviewed by the group and this review generated valuable dialog which increased the overall robustness of the lunar architecture. More information on the ISECG Reference Architecture for Human Lunar Exploration can be found in the paper, *IAC-10-A5.2.9, An International Strategy for Human Exploration of the Moon* (Ref 1).

This section reflects a high level summary of how certain ISS lessons learned were reflected in the work to define an international lunar exploration reference architecture. It also identifies critical issues that the IAWG identified. The lessons below are presented in order of their occurrence in the ISS Lessons Learned document, and also reflect the ISS numbering scheme.

1-Lesson: Accommodate Partner's Own Objectives

Over 600 initial lunar exploration objectives were collected from 9 ISECG agencies (BNSC, CNES, CSA, DLR, ESA, JAXA, KARI, NASA, NSAU). There was a high degree of overlap/synergy among many of the objectives. From analysis of these objectives, the ISECG was able to identify 15 common goals (Ref 2). Each agency was able to see how their objectives could be met through the ISECG reference architecture.

2-Lesson: Establish Realistic Expectations

At the time of development of the reference architecture, due consideration was given to

realistic cost, development schedule, and achievability of the ISECG Reference Architecture for Human Lunar Exploration. Participating agencies recognized that the ISECG architecture was not the minimum lunar exploration scenario and strove, at the time, for a robust scientific exploration program. Subsequently, the global economic crisis influenced available funding and delayed achievement of a lunar exploration scenario. Now, planned robotic missions to the moon will greatly increase scientific knowledge and allow a more targeted lunar exploration campaign. This overall situation reinforces the importance of this lesson.

3-Lesson: Employ Design Reference Missions to Define Requirements

The ISECG Reference Architecture for Human Lunar Exploration reflected a significant effort by participating agencies and was useful in identifying potential partnerships. This experience led agencies to recognize the importance of an international exploration scenario to focus global efforts in preparing for exploration beyond low Earth orbit. A pictorial representation of one phase of the scenario is shown in Figure 2.

4-Lesson: Use Clear Mission Objectives to Drive Support

The importance of identifying clear and compelling goals was a major area of emphasis in the ISECG common goals development process.

7-Lesson: Establish Appropriate Interdependencies

The critical importance of interdependency was recognized as a significant consideration through the lunar architecture work. While the lunar architecture included many opportunities for critical contributions by multiple agencies in order to meet lunar exploration objectives, the main cost driver (i.e. the transportation system) was provided by NASA. The IAWG recommended that agencies start a dialogue at senior agency management level on the benefits and challenges of interdependency. Funding challenges faced by all agencies indicate that a serious discussion of interdependency strategies should take place as early as feasible. An interdependency strategy should, for a given reference mission scenario, at least define (1) areas in which interdependency is beneficial or required and for what reasons, (2) conditions to be met for making interdependency acceptable to all Partners and (3) an initial assessment of the possible roles of Partners.

11-Lesson: Plan for an Evolving Public Policy

Space agencies must operate and maintain commitments in a world where public policy shifts within their country cannot be avoided. The retirement of the U.S. Space Shuttle is a good example of this. Retirement of the Shuttle had an impact across the ISS Program. The lunar reference architecture reflects the attempt to take this into consideration by definition of exploration phases which could allow partners to maintain, add or reduce their contributions to lunar surface exploration.

12-Lesson: Employ a Robust Design

Multilateral function teams within the IAWG were asked to identify critical functions and explore concept for providing robustness to the lunar architecture. The IAWG examined concepts in transportation, mobility and habitation in order to provide additional robustness to the architecture. Furthermore, special attention was given to the assessment of modularity concepts, redundancy strategies and contingency scenarios.



Figure 2: Pictorial representation of the Polar Relocation Phase of the ISECG Reference Architecture for Human Lunar Exploration.

13-Lesson: Apply Common Standards and Tools for Developing Interfaces

The ISECG Reference Architecture for Human Lunar Exploration was analyzed by the multilateral function teams to identify interfaces that can benefit from standardization. Several opportunities were identified.

17-Lesson: Minimize External Interfaces to End-to-End Systems

The IAWG noted that the recommendation to ensure that a single partner can manage all internal interfaces is ideal yet may conflict with the interdependency strategies needed to enable a robust space exploration program.

20-Lesson: Use Dissimilar Redundancy in Systems for Program Flexibility and Stability

The IAWG noted that it may not be financially practical to have certain critical functions provided by multiple agencies as the cost of developing systems capable of reaching the moon is extremely high and may have little synergy with what is needed to exploit low Earth orbit, or other destinations. Decisions on where to invest in robustness that improves crew safety and programmatic stability should be made with this in mind and by all participating agencies.

42-Lesson: Include Tangible Benefits with Early Visibility to the Public

High priority was placed on identifying programmatic and public outreach milestones that demonstrate tangible benefits to the public. A concrete goal was defined to reflect this priority and it was used as one of several key discriminators in campaign selection (A lunar exploration campaign defines a sequence of robotic and human missions to the lunar surface in a well defined time period for addressing a set of lunar exploration objectives).

43- Lesson: Plan Early Achievements to Sustain Political Support

High priority was placed on early achievements, such as the inclusion of and reliance on a robotic precursor phase. A goal has been defined to reflect this priority and it has been used as one of several discriminators in campaign selection.

55-Lesson: Considering Commercial Engagements Early in the Process and Determine the Best Stage to Pursue

The IAWG recognized that some architectural elements were well suited for commercial services and expected that agencies who establish international agreements to implement a lunar exploration campaign would further advance these opportunities at the right time. The IAWG did recognize a critical issue in that the international nature of exploration missions would dictate a common strategy for commercial engagement.

ISS LESSONS LEARNED GUIDING EXPLORATION MISSION SCENARIOS

With the cancellation of NASA's Constellation Program, specific planning for exploration of the Moon was stopped. The priority was placed on identification of exploration capabilities which would allow astronauts to visit near Earth asteroids, the Moon and ultimately Mars. Reflecting this overall global situation, 12 agencies participating in ISECG have developed

the Global Exploration Roadmap (GER). The GER reflects a global human space flight road mapping effort, intended to provide a technical basis for informing decisions on exploration activities.

The GER reflects a common exploration strategy, leading to human exploration of Mars. This

strategy starts with the ISS as the current destination for human spaceflight, but also as an important platform for advancing the technologies, capabilities and operations concepts needed for deep space exploration. The strategy is depicted in Figure 3.

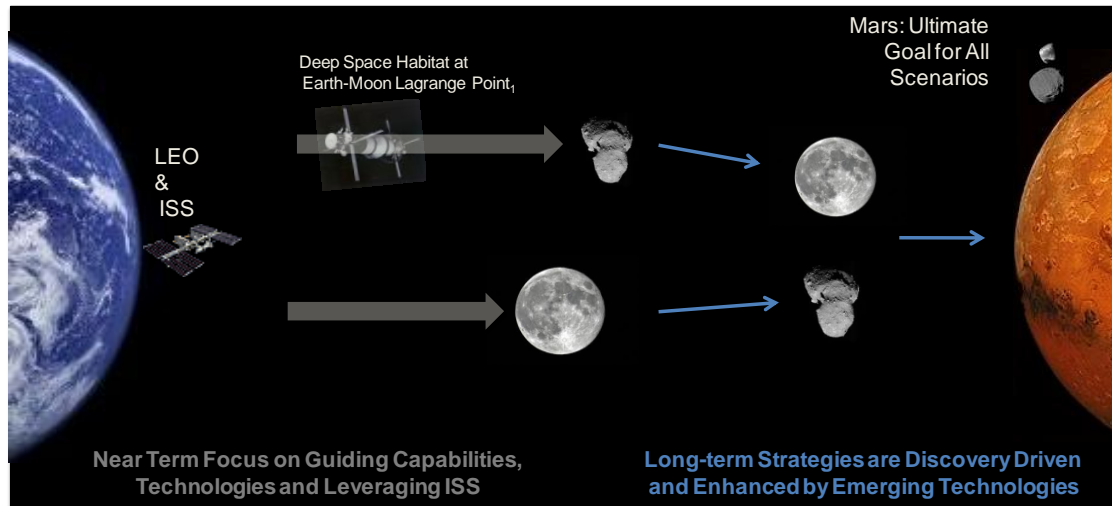


Figure 3: Two pathways in a Common Exploration Strategy

With the common strategy, agencies agree there are several pathways to Mars. Either Moon-next or Asteroid-next are considered feasible pathways. In order to translate the pathways into reference missions and campaigns, the ISECG has developed ‘Mission Scenarios’. These mission scenarios reflect logical sequences of missions to explore the Moon or near Earth asteroids, while advancing technologies and capabilities needed for human missions to Mars.

Where the ISECG lunar architecture was a detailed (pre-phase A) conceptual architecture, the GER mission scenarios are top level sequences of missions. Because there is much work to be done to expand on the specific design reference missions contained within a mission scenario, evaluation of many specific ISS Lessons Learned is premature. However, the most important lessons which drive scenarios have been considered and this work is summarized in the table below.

No.	ISS Lesson Learned	Influence on GER Mission Scenarios
1	Accommodate Partner’s Own Objectives	Agency goals and objectives were collected and mapped to exploration destinations.
2	Establish Realistic Expectations	During the development and assessment of the mission scenarios, realistic cost and development schedule were considered.
3	Employ Reference Missions to Define Requirements	Each mission scenario contains design reference missions which allow partners to ensure that defined capabilities successfully allow goals and objectives to be met.
7	Establish Appropriate Interdependencies	Because international partnership is essential and beneficial for human space exploration, enabling early and visible partnerships was important in developing and assessing the mission scenarios. The number of astronaut flight opportunities, a key benefit to every agency, was one of the major indicators.
9	Redundant Transportation Commitments	This lesson is a major cost driver to exploration

		<p>scenarios, so the ISECG considered only realistic contributions tied to mission scenario timeframes. As a result, US Space Launch System (SLS) and Multi Purpose Crew Vehicle (MPCV), and Russian New Generation Spacecraft and New Generation Space Launch Vehicle (NGSLV) were introduced as the dissimilar redundant crew transportation capabilities for some missions in the mission scenarios.</p>
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ISS LESSONS LEARNED TO MAXIMIZE THE BENEFITS OF EXPLORATION MISSIONS

Any exploration mission should have clear goals and objectives. For the ISS, one of the main goals pursued by all partners has been implementation of a broad and ambitious national scientific research programs. Important lesson learned from the ISS utilization is apparent necessity to coordinate scientific programs of all partners. Dedicated international science working groups were formed early in the ISS partnership to coordinate utilization activities at the agency science level. These groups enabled international technical and scientific collaborations at the ISS development stage already. A very important step has been making this effort sustainable throughout the life cycle of the program. Historically, the ISS Russian and U.S. segment utilization programs were not strongly coordinated at the beginning of the ISS utilization phase. This caused some duplication in the national research programs and some payloads onboard the ISS. However, life has adjusted this situation and now at the eve of full scale ISS utilization, many ISS scientific projects involve scientists from various partner countries, despite that they are running in the frame of a respected partner national program. Yet more similar projects are under preparation phase now. ISS partners enter in bilateral and multilateral agreements on a “non funds exchange basis” with researches interesting for all participants. See figure 4.

A smart balance between national and international parts of the common utilization program is a key issue ensuring successful achievement of declared goals in any international exploration initiative. New exploration missions, such as to the Moon, asteroids and Mars, are expected to be even more expensive than the ISS. Therefore, early planning and implementation of technology demonstration and research programs within a

future exploration mission on multilateral coordinated level will definitely reduce costs of the enterprise and make it more effective. It will ensure that the collective investments of all partners deliver the maximum benefits to each participating country.



Figure 4: Cosmonaut S. Volkov runs joint Roscosmos-ESA experiment “Plasma Crystal” on ESA facility installed in Mini-Research Module of the ISS Russian Segment.

CONCLUSION

The ISS Lessons Learned have been a rich source of information for guiding ISECG work on the ISECG Reference Architecture for Human Lunar Exploration and more recently the development of the Global Exploration Roadmap. The ISECG developed products reflect the importance of these lessons, but also highlight critical areas which require further analysis. Such additional analysis is in particular required for three of ISS Lessons Learned: establish realistic expectation, establish appropriate interdependence and provide for redundant transportation commitments. A common issue for all these lessons is affordability. Affordability is driven by available budget, but also expected returns.

An assessment of affordability, in particular in a pre-program formulation stage and at international level, is challenging. In any case, the degree of interdependency required for successfully and sustainably implementing human exploration missions beyond low Earth orbit at international level exceed most likely the degree of interdependency experienced today within the ISS Program. Part of this is the ability to provide redundant transportation capabilities. In a human exploration mission to Moon or an Asteroid, well above 80 % of the costs are related to transportation. Full redundancy of all transportation functions will therefore be difficult to achieve. During the initial exploration phase, large infrastructure will not exist in deep space or on other planetary surface, possibly limiting the need for redundant transportation to ensure access and continued operations/ utilisation of such infrastructures. Redundancy consideration will therefore be primarily driven by the need to ensure overall program robustness and the safety of crew in space.

ISECG is committed for its future work to not just further consider and analyse the ISS Lessons Learned, but also advance the international understanding on the strategic considerations in the critical areas discussed above.

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