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THE GLOBAL EXPLORATION ROADMAP AND EXPANDING HUMAN/ROBOTIC EXPLORATION MISSION COLLABORATION OPPORTUNITIES

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The *Global Exploration Roadmap* (GER) is a human space exploration roadmap that recognizes the importance of increasing the integration and collaboration between human and robotic explorers. The GER is a product of the International Space Exploration Coordination Group[1] and represents a high level status of the collaborative work of engaged space agencies to prepare for the future of human space exploration. Since the August 2013 release of the updated GER, space agencies have continued this exchange, welcoming the addition of China as an active participant as well as advancing the definition of near-term exploration activities. This paper will describe the work of participating space agencies over the last year with a special focus on those activities which strengthen the human/robotic exploration partnership.

As they plan for sustainable exploration missions, agencies are continuing a strong focus on creating opportunities for further integration and collaboration between human and robotic elements where it makes sense to do so. Success will come from increased understanding and leveraging of the unique contribution which human explorers can bring to meeting science objectives. This will require engineering trades and assessments which balance science with other human exploration objectives. This work is considered timely and critical because strengthening the human/robotic partnership will bring an increased set of benefits to each community over time and therefore strengthen stakeholder support for space exploration, both human and robotic. At the same time, it helps agencies to increasingly leverage synergies of technology developments and mission planning to exploration destinations within the respective agencies' programmes.

This paper will highlight the coordination of agencies in two areas which advance human space exploration objectives and are of interest to the science community. The first area is human-assisted sample return, where humans in the lunar vicinity can capture and return samples collected robotically from any destination in the solar system. Agencies have defined mission concepts for lunar and Mars sample return which may create a range of benefits to human exploration and science communities that merit further consideration; technically, programmatically and geopolitically. The second area revolves around the effort to further understand the nature and distribution of lunar polar volatiles. The widespread interest in these volatiles creates an opportunity to coordinate the activities of space agencies and other entities to fill science and exploration knowledge gaps. The paper will expand on the rationale for investigation of lunar polar volatiles in the context of the GER, and describe the efforts of space agencies towards that end. Lastly, the paper will take the opportunity to discuss the outlook for a future update of the GER.

[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.

INTRODUCTION

As ISECG agencies continue to prepare for future human exploration missions, it remains a priority to increase coordination between human and robotic exploration programs and efforts. The first sustainable step for humans beyond low-Earth orbit will be into cislunar space. These missions will be realized by investments in multi-destination exploration capabilities such as SLS, Orion and a habitat system that serves as a precursor for a human exploration spaceship. The presence of humans and their infrastructure in cislunar space not only prepares for follow-on missions to the lunar surface and beyond, but will also provide opportunities for advancing concepts which strengthen a human-robotic exploration partnership.

Robotic missions to the moon continue to be planned by several space agencies. These missions may be enhanced by human space exploration capabilities deployed in cislunar space. Capabilities such as communication relay, low-latency control and others. Lunar robotic missions also provide the opportunity to test systems and capabilities which may be extended to future human systems, such as planetary surface landers and local resource prospecting. The same can be said for NASA’s asteroid redirect mission - a proposal to relocate a small asteroid boulder to cislunar space to create opportunities for science and technology demonstration, while learning more about exploration of low-gravity bodies.

ISECG is pursuing several activities which strengthen the integration between human and robotic exploration activities on and around the moon. The specific intent is to create opportunities to realize a wider set of benefits for stakeholders and highlight opportunities for new missions. These opportunities may be in the form of partnerships to execute a particular robotic mission. They could also take the form of information that helps individual agencies make decisions to pursue new mission objectives, technologies or activities.

Current ISECG activities are focused in two areas which are considered timely and high value to participating agencies. The first activity is revolves around a joint study of a series of robotic missions which are enabled by the presence of humans and their infrastructure in cislunar space. The robotic spacecraft and mission design is intended to serve as an early precursor to a human lunar lander and test a limited number of technologies which could be used on a human scale lander. The integrated human and robotic mission will obtain science data and samples of interest to the science community. In addition, a concept for human-assisted Mars Sample Return has been elaborated by NASA. In this case, a variant of the reference concept for Mars Sample Return is based on human retrieval of the Mars sample in a stable cislunar orbit. By assessing these studies, ISECG hopes to make recommendations regarding how human cislunar infrastructure can provide a standard approach for human-assisted sample return.

The second area of ISECG attention relates to a focused activity to expand collaboration and coordination in the assessment of lunar volatiles, and water ice in particular. How can information and capabilities be shared in order to strengthen the ability of missions planned or under study by agencies and the private sector contribute information related to filling strategic knowledge gaps related to lunar volatiles.

The updated Global Exploration Roadmap (GER), released in August 2013 (Ref 1), provides a common reference which is useful for the work of individual space agencies to advance mission concepts and study associated capabilities. Anchored by planned robotic and human missions and related investments, innovative concepts can be explored which add to the value of these planned missions and create opportunities to realize additional missions. Results from these collaborative activities in ISECG may be used by individual mission owners during mission formulation and planning work to achieve a higher return for investments. In the past, robotic mission owners have been space agencies, but today and increasing number of private entities are planning or evaluating possible exploration missions. The ISECG work is intended to be a resource for private mission planners looking to increase the overall global impact of their activities.

CONTINUING WORK ON A HUMAN SPACE EXPLORATION ROADMAP

Before expanding on ISECG work in the area of the human/robotic partnership, it is worth providing a short overview of the nature and significance of the ongoing road mapping work. The GER reflects an international long-range strategy for future human exploration missions. This common strategy begins with the International Space Station to prepare for exploration and leads to a sustainable human exploration on the surface Mars. The Global Exploration Roadmap (figure 1) emphasizes international coordination in the near-term initiatives in implementing the common international strategy, namely: 1) fully utilizing the ISS to prepare for exploration and benefit humanity, 2) continuing efforts to enhance coordination between human and robotic missions, and 3) discovery-driven missions in the lunar vicinity that evolve capabilities and techniques needed for Mars, while enabling discoveries on the Moon and near-Earth asteroids.

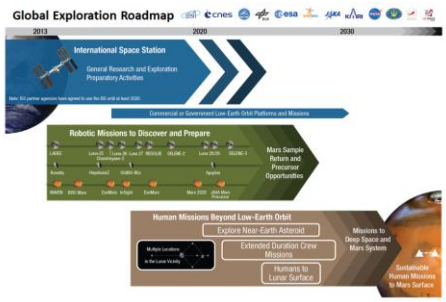


Figure 1: The Global Exploration Roadmap

The journey to Mars is a long one. ISECG focuses on continuing definition and elaboration of a common long-term strategy making it clear there is a role for any nation willing to contribute. ISECG also evaluates concepts and opportunities as humans prepare the next steps in a sustainable long-term program of exploration: specifically, movement outward from low-Earth orbit (LEO) into cislunar space. International partnerships will enable these missions and the unique capabilities of humans to advance knowledge, inspire, foster promising commercial opportunities and prepare for the next steps. For a deeper understanding of the breadth of current work ongoing within ISECG, see *International Missions to Lunar Vicinity and Surface – Near-Term Mission Scenario of the Global Exploration Roadmap*;, B. Hufenbach et.al (Ref 2).

Within ISECG, an expanded set of participating space agencies is engaged to various degrees. China is a recent addition to the group of participants. The addition of China as a participant in this work may create near-term collaboration opportunities on Chinese robotic missions, and the Chinese space station. While they are not currently engaged in the human exploration conceptual work, Chinese contributions have the long-term potential to enhance of the global exploration endeavour and Chinese participation in ISECG is welcomed by all participating agencies.

HUMAN-ASSISTED ROBOTIC EXPLORATION AND SAMPLE RETURN

Human-assisted robotic mission concepts are receiving increased attention by participating agencies within ISECG because they appear to provide opportunities for leveraging the unique capabilities of human exploration to achieve multiple objectives, including achieving high priority science objectives such as sample return (Ref 3), while serving as precursors for future human missions to planetary surfaces. Work remains to fully quantify and assess this benefit, but several ongoing studies seek to provide data to complete such an assessment. Two studies in particular, one led by ESA and one led by NASA/JPL are ongoing and shared within ISECG. The ISECG review and assessment serves to raise awareness of these proposed mission concepts and seek consensus on the value of each concept. If synergies exist between the concepts and this synergy can be leveraged to increase the possibility of realising the missions (or similar missions), then ISECG will document the results in the next iteration of the Global Exploration Roadmap. The two studies are summarized below.

Human Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES)

ESA is leading an international study called HERACLES. The goal of the study is to design an end-to-end human-robotic architecture demonstrating how multiple objectives of human and robotic lunar exploration can be met by such architecture. It involves participation from the Canadian Space Agency (CSA), Japan Exploration and Space Agency (JAXA), NASA and Roscosmos. The study seeks to understand the performance of an architecture based on cislunar infrastructure and how it enables satisfaction of the goals and objectives of the GER. The cislunar infrastructure includes a deep space habitat, such as described in the GER, and robotic mission components such as a lander and medium size rover. With this architecture, the study seeks to identify a series of missions which demonstrate how such an architecture can prepare for future human lunar landers and how it can address priority science goals. In addition, the study considered how does the architecture yield useful information regarding application of telepresence for future exploration destinations.

The study was divided into in several steps. The first step was to define fully coordinated goals and objectives as well as design principles. The goals and objectives fall into three main categories:

- Prepare human exploration of the lunar surface
- Enable scientific and exploration knowledge gain
- Provide opportunities to advance Mars sample return scenarios

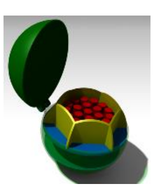
Design principles were also identified and listed here:

- Achieve balance of the architecture goals
- Thrive for minimum complexity in the overall architecture (e.g. the elements of human spaceflight infrastructure, operations, robotic elements)
- Advance human-robotic partnership
- Maximise cooperation opportunities
- Provide opportunities for commercial services

The second step of the study focused on the lander design concept. A special emphasis was put on driving out opportunities for reducing risk in the development of a future human lunar lander. While the scale of the two landers (robotic and future human lander) is significantly different, there were several possibilities identified. This lead to a system-level design of an automated (potentially tele-operated) lander with the following capabilities:

- Long-life (> 4 y) reusable ascent stage (600 kg)
- Long-range fast mobility rover optimised for tele-operated sample retrieval (500 kg)
- Lightweight high thrust descent stage (1,500 kg)
- Docking system compatible with the cislunar habitat
- At a total wet mass of 10,000 kg, the lander can support various launch scenarios including a split launch on Soyuz / Ariane (assembly at the cislunar habitat) or co-manifested launch on SLS Block IB.

Of particular significance is the design of the sample container. Its design has been specifically selected so as to be compatible with the Mars Sample Return sample container. See Figure 2.



- Optimised for sample quality and preservation
- Similarity to Mars sample return
- 1 kg cryo sample capability
- 2h of autonomous operations

Figure 2: Sample Container Design Concept

Given the system design of the architecture elements, a mission campaign was developed to demonstrate how these elements are used to address the goals and objectives in the frame of multiple missions (assumed to be 4 missions for the purpose of the study) of the lander to the lunar surface. The crew on the ground and on board the cislunar habitat supports the surface operations through tele-operations in sampling and driving. Samples are delivered by the reusable ascent stage to the habitat, where they are transferred to the crew vehicle for return to Earth, allowing a high level of sample preservation (max. temperature <140K). A replacement descent stage delivered to the habitat and linked with the ascent stage enables the next mission. Since the rover is driven by ground-control to the next landing site on the surface, the replacement descent stage can carry 500 kg worth of user payloads. In the mission campaign under consideration by a team at the Lunar Planetary Institute/LPI (D. Kring et al.), three landings in the Schrödinger basin that lies at the southern edge of the South Pole Aitken Basin could cover high priority science objectives in lunar geophysics and fundamental science (Ref 4). A fourth mission to the South Pole region could carry a second rover to support the sampling of volatile and/or resource-relevant material.

With this architecture and mission design, the benefits of the human-robotic architecture were found to be:

- Certification and flight test of actual technology elements of a human lunar architecture in actual operational conditions
- Design relevant for other critical elements of the human lunar architecture and potential roles for international partners
- More sustainable and affordable than a series of stand-alone missions
- Ten times more efficient mobility (3 km/kWh when crew-controlled) compared to autonomous approaches
- All top-level globally agreed high-priority lunar science objectives (Ref 4, Ref 5) addressed
- High operational robustness in darkness and cold temperatures

Human-Assisted Mars Sample Return

NASA/JPL is leading the study of a human-assisted Mars sample return mission concept. A reference scenario for a robotic Mars sample return series of missions was elaborated by an international working group, iMars (Ref 6). The JPL human-assisted Mars sample return study builds on the international architecture and assesses the benefits of putting humans in the loop. The iMars concept for Mars Sample Return (MSR) assumes four elements, each representing a significant investment. First, a robotic mission to the surface of Mars obtains and caches sample for later return to Earth. Second, a sample return orbiter is emplaced in the orbit of Mars. The third element is a mission to retrieve the cached sample from the surface of Mars and deliver it to the sample return orbiter. The fourth element is one or more sample receiving facilities to promote Earth-based study of the returned samples. The JPL human-assisted Mars sample return (HAMSR) study assumes the success of the Mars 2020 mission to collect and cache samples of interest to the science community. Details of near-final study results have been shared in a paper presented to the Institute of Electrical and Electronics Engineers in 2015, *Human-Assisted Mars Sample Return*, Gershman et.al (Ref 7).

Crew participation in the Mars sample return scenario offers the opportunity to mitigate two major challenges of a Mars sample return mission. They can assist in sample containment, addressing a subset of planetary protection guidelines having to do with protecting planet Earth. They can also contribute a reliable and relatively smooth Earth entry, descent and landing capability. Whether a HAMSR approach leads to a faster or less costly realization of Mars sample return is open for debate. The case can be made that adding the human element provides the momentum and other non-tangible benefits which lead to realization of a Mars sample return mission earlier than previously assumed.

The JPL-led HAMSR study is operating with the following assumptions:

- The goal is to enable human-assisted sample return from multiple destinations, e.g. moon, outer planets, comets, etc.
- Humans will use cislunar space as proving ground for future deep space missions and the presence of the crew and infrastructure should be used to meet other exploration and science objectives.
- Human-assisted Mars Sample Return would be a significant objective of the human mission in cislunar space, but not the only objective of a mission.
- Provide a simple and affordable human infrastructure design solution
- Notional Sample Return Orbiter (SRO) would be "clean" when it reaches Earth-Moon system

A large number of possible cislunar human capture architectures was identified. Using the assumptions listed above, the list of possible options was narrowed significantly and the study focused on five scenario options outlined in Table 1. Each of the five scenario options is briefly summarized.

Scenario	3B	5A	5D	5J	6E
Pickup by					
Orion - free flying OS	x				
Habitat - free flying OS		x	x		
Habitat - docked/berthed to SRO, OS handed off				x	
Logistics Module, remotely piloted					x
When					
On way to Hab					x
At or near the Hab		x	x	x	
On way home	x				
Capture/ingress					
Simplified Scenario 3 hatch/removable container	x	x			
Through open hatch (depressurized)			x		
EVA from Hab, grab OS				x	
Special compartment on LM hatch					x
Transfer to Hab	n/a	n/a	n/a	n/a	
With cargo					x
Stowing & containment during reentry					
Internal vault	x	x	x	x	x

Table 1: Definition of HAMSR scenarios

Scenario 3B - Capture by Orion

Scenario 3B relies on Orion to capture the Mars sample container, using a special hatch as illustrated in Figure 3. The Sample Return Orbiter releases a 20-cm spherical encapsulated Mars sample container approximately 1-2 km from Orion, which tracks the container using onboard capabilities. The sample container is engulfed in a bucket built into the Orion docking hatch. The crew accesses the bucket from inside the Orion and removes the sample container to a special vault designed to protect the sample container during reentry, as illustrated in Figure 4.

Figure 3: Orion with special hatch approaching sample container

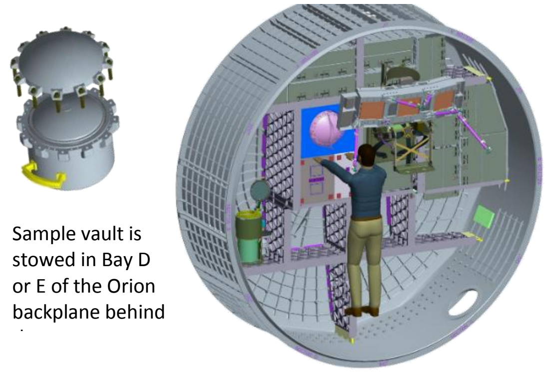


Figure 4 – Crew stowing sample container after Capture (Conceptual Design)

Scenario 5A - Capture by Hab using Hatch Bucket

The variants of Scenario 5 involve capture of the sample container by a crewed Habitat stack, which is maneuvered by a docked Orion. In Scenario 5A (illustrated in Figure 5) the sample container is captured in a hatch bucket similar to Scenario 3B. The SRO releases the sample container at a distance of approximately 100 m. The crew uses a lidar sensor and a centerline camera to locate the sample container and assist its capture. The procedure for sample handling after capture is the same as that described in scenario 3B. This hatch could be larger than the Orion hatch. In that case, the bucket could be designed to handle a larger sample container.

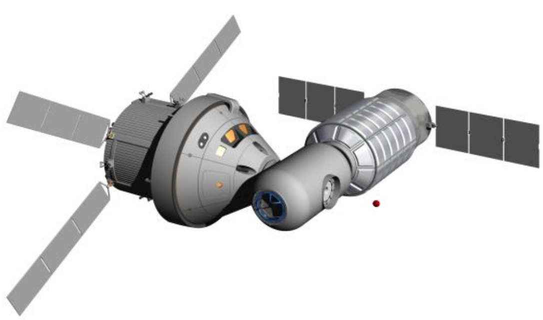


Figure 5 – Scenario 5A – Capture by Hab using Hatch Bucket (Conceptual Design)

Scenario 5D - Capture by Hab via Airlock

In Scenario 5D (Figure 6), an airlock would be depressurized and two suited crew would wait for the sample container. The SRO would release the sample container about 100 m away and the crew would maneuver the stack to engulf it through the hatch where the crew would handle it, by hand or with some simple catching device. Again it would be placed in a vault and stowed in Orion.

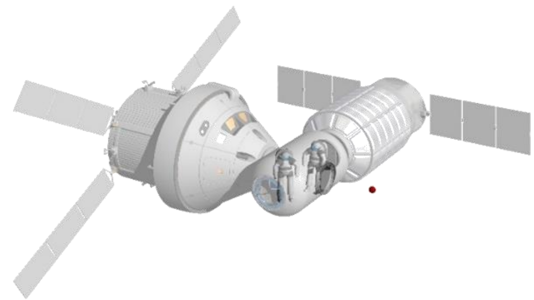


Figure 6 - Scenario 5D – Capture by Hab via Airlock (Conceptual Design)

Scenario 5J - SRO Docked with Hab

In Scenario 5J, the SRO is equipped with a docking ring so that it can dock with the human infrastructure stack upon arrival (Figure 7). The sample container would then be handed off to suited crew through the open hatch by a device on the SRO. The rendezvous and docking of the SRO to the human infrastructure is considered to be within the basic requirements of the SRO, as it must rendezvous and capture the sample container in Mars orbit.

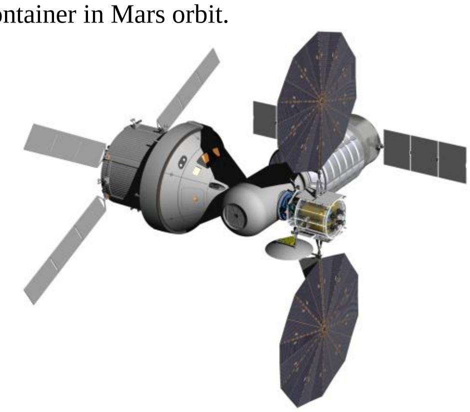


Figure 7 – Scenario 5J – SRO Docked with Hab (Conceptual Design)

Scenario 6E - Logistics Module

In scenario 6E, the sample container is transferred from the SRO to an uncrewed logistics module en route to the human infrastructure/habitat using a hatch bucket similar to Scenario 3B (Figure 8). The transfer would likely be controlled from Earth. Once the logistics module is docked to the habitat, it would wait for the crew to arrive. The crew would open the outside door of the logistics module hatch bucket and remove the sample container prior to fully opening the hatch to access cargo.

Figure 8 – Scenario 6E – Logistics Module (Conceptual Design)

In summary, a strong partnership between the human and scientific exploration of Mars will increase the value of NASA investments to all stakeholder groups. The first steps in building this partnership have been taken with the Mars Curiosity and Mars 2020 missions. Human-assisted Mars Sample Return provides the opportunity to cement a lasting partnership which will bring measurable benefits to both the human exploration and science communities. Human-assisted Mars Sample Return relies on the presence of crew in cislunar space to collect, inspect and return samples recovered robotically form the surface of Mars. Benefits to this approach can be found in 3 main areas, listed below. The main stakeholder benefiting is listed in parentheses:

1. Increased probability that investments in Mars Sample Return will return scientifically interesting sample back to Earth (science community)
2. Increased confidence in sample containment (science community)
3. Knowledge and validation of planetary protection approaches which will simplify human Mars surface mission definition (human spaceflight community)

ISECG participants have been following the JPL-led study. They will compare the two different approaches (HAMSR and HERACLES) to human-assisted sample return looking for commonality in the required features of the human spaceflight infrastructure items.

EXPLORING LUNAR VOLATILES

Use of local resources present on the Moon, asteroids and Mars will limit the cost and complexity of bringing all the needed supplies from Earth and contribute to the long-term sustainability of human space exploration. More information is needed before exploration architectures which rely on the use of local resources in the near-term can be chosen. Further study of lunar polar volatiles provides the opportunity to answer existing exploration architecture questions, while providing knowledge of great interest to the international science community. Operational use of resources obtained from the Moon or asteroids is not envisioned in the ISECG mission scenario at this time. However, agencies are interested in fully understanding the potential of these resources within the constraints of their current budgets.

Such a reality gives rise to ISECG's effort to promote collaboration and cooperation in filling strategic knowledge gaps (Ref 8) through a web-site based effort. Planned and possible lunar robotic missions, combined with the presence of crew in the lunar vicinity offer the opportunity to answer common questions related to the nature and distribution of lunar polar volatiles of interest to many stakeholders. The idea is to facilitate collaboration and enable cooperation which brings the maximum resources to bear in seeking data related to polar volatiles and their usability to address the needs and desires of the human spaceflight and science communities. Given the interest of participating agencies to support private sector initiatives which contribute to economic expansion, it is expected that some players in the private sector are stakeholders in this activity as well.

The ISECG created a special team comprising representatives from several interested space agencies. This team has assembled a comprehensive set of literature on the state of knowledge regarding polar volatiles. They have also included resources which summarize available information and make recommendations, such as the recent specific action report by the Lunar Exploration Analysis Group on lunar volatiles. The team has assembled information regarding planned or conceptual missions to the lunar polar region, as well as information on existing instruments of interest for lunar prospecting. All this information will be posted on the ISECG lunar volatiles website (figure 9), accessible from the ISECG website www.globalspaceexploration.org.

In addition to keeping information up to date, the agencies participating in the effort seek to arrange virtual workshops to address questions related to the effort to stimulate collaboration and coordination. Potential questions include:

1. Is there a region of interest most likely to enable answers to questions of interest by multiple stakeholders?

2. What additional data sets are needed to understand the nature and distribution of polar water ice?
3. How data is best obtained?
4. What additional data sets are needed before investment in missions to test resource extraction techniques?
5. Are there opportunities for common infrastructure to lower the cost of accomplishing any single mission, thereby opening opportunities for more players?
6. What is the available hardware set (in agencies, academia, and industry) which can be used for individual mission needs?

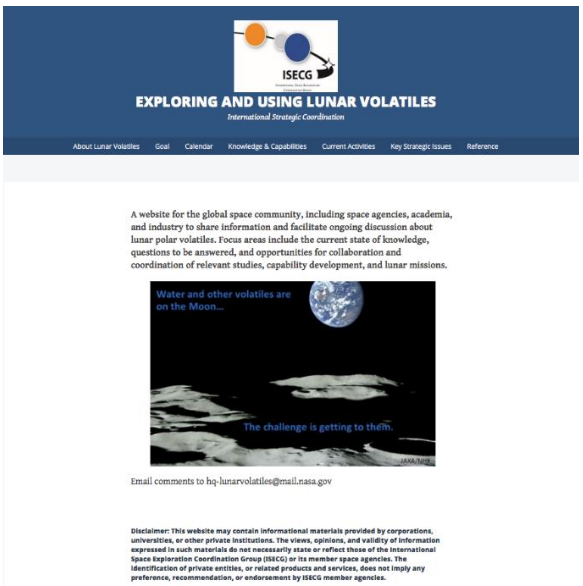


Figure 9: Screen shot of ISECG lunar volatiles website

CONCLUSION

Agencies participating in the ISECG continue to actively seek meaningful and effective approaches to increasing the synergy between human and robotic missions for the benefit of each community. Concepts such as human-assisted sample return may prove to significantly increase our knowledge of the solar system and its formation by enabling a significant increase in the amount of sample which can be returned to Earth for study. Lunar polar volatiles may be accessible in a safe and cost effective manner, opening opportunities for more sustainable exploration architectures and other commercial uses. Studying the challenges and opportunities in these areas is a focus of ISECG.

Governments participating in the International Space Exploration Forum (ISEF) held in January 2014 supported the work of ISECG and the Global Exploration Roadmap, in particular. The meeting results are captured in a *Forum Summary* (Ref 10). Nations represented at the ISEF recognized the value of human space exploration for its ability to drive technology and innovation, positively impact economic growth, and inspire our youth. The importance of international cooperation was stressed, reflecting the consensus that space exploration is a global endeavor needing the expertise of many nations. Participants in the ISEF stressed the importance of increasing the synergies between human and robotic exploration missions. For this reason, ISECG continues to look for ways to strengthen human robotic mission collaboration. The next meeting of the ISEF will be hosted in Japan in 2017. The specific timing of the meeting has not been determined yet but the hope is that government representatives meeting in Japan will continue to note the positive work performed in the ISECG to create cooperation and collaboration opportunities, consistent with the priorities expressed by governments.

In order to maintain the GER as an up to date reference for the exploration plans and mission concepts under consideration by space agencies, it is planned to be updated regularly. The next planned update of the GER will occur in early 2017. This timing has been chosen so as to be a timely influence on space agency efforts to secure political and programmatic support for their proposals to implement near-term mission scenarios.

ACKNOWLEDGEMENTS

In general, the work of ISECG would not be possible without the various conceptual studies and related work performed by participating agencies, either individually or in partnership. In the case of ISECGs work advancing the human robotic exploration partnership, it is especially true. The authors would like to recognize the outstanding work of ESA/Markus Landgraf and his HERACLES team and JPL/Robert Gershman and his entire Human-Assisted Mars Sample Return (HAMSR) team, including JPL/Scott Howe and Gregory Lantoine, JSC/Stan Love, Lockheed Martin Corporation/Josh Hopkins and Mike Drever. The authors also would like to recognize NASA/Nantel Suzuki and John Gruener, and ESA/James Carpenter for their outstanding leadership of the ISECG lunar volatiles special action team.

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