IAC-14-A.3.1.1

INCREASING SYNERGIES BETWEEN HUMAN AND ROBOTIC EXPLORATION MISSIONS AS ENVISIONED IN THE GLOBAL EXPLORATION ROADMAP

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Human exploration of the solar system will proceed in a step-wise manner that builds on the capabilities supporting ongoing human spaceflight programs such as the International Space Station and the Chinese space program. Exploration missions will allow agencies to advance their capabilities to meet individual and common goals and objectives. Space exploration goals and objectives reflect the reasons why we choose to explore space with humans, bringing benefits to people on Earth. Robotic capabilities not only prepare the way for future human missions, but maximize the impact of human explorers. Building on this natural synergy is important and was strongly supported by government representatives at the International Space Exploration Forum, held 9 January 2014 in Washington, DC. In its updated *Global Exploration Roadmap* (GER), the participating agencies of the International Space Exploration Coordination Group (ISECG)[1] demonstrate their commitment to defining and implementing meaningful steps towards advancing human and robotic mission integration.

In the work planned in 2014, ISECG has established several priorities for increasing synergies between human and robotic missions. Participating agencies continue their human spaceflight road-mapping activity with particular focus on advancing the definition of the near-term missions in the lunar vicinity and concepts for accessing the lunar surface. The three mission themes each provide concrete opportunities for human and robotic collaboration: (1) Exploration of a Near-Earth Asteroid, (2) Extended Duration Crew Missions and (3) Humans to the Lunar Surface. This paper will describe work to advance the definition of each mission theme and focus on the roles of and approaches for robotic and manned activities. Agencies hope that collaborative discussions within ISECG contribute to the realization of these opportunities. Among the concepts to be discussed are:

- Human-assisted sample return: using the presence of crew in the lunar vicinity to return samples of asteroids, the Moon and Mars;
- Expanding the global understanding of the nature, distribution and usability of lunar polar volatiles;

In addition to the technical work of ISECG, the paper will discuss the importance of increasing human and robotic mission synergies in order to win government support and funding to advance space exploration goals. Lastly, the paper will also take the opportunity to share the status of space agencies' stakeholder engagement activities and an outlook for future update of the GER.

[1] In alphabetical order: ASI (Italy), CNES (France), CSA (Canada), 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

Exploration of the solar system will benefit significantly from the increasing global efforts to coordinate objectives and plans of human and robotic missions to destinations humans may someday live and work. The partnership between human and robotic missions dates back to the early 1960's. Both US and Soviet lunar probes returned information critical to the planning and/or implementation of human lunar exploration missions. Today, initiatives like the ISECG Global Exploration Roadmap create opportunities for expanding coordination in ways which are advantageous to both robotic and human mission owners. Considering destinations where humans may someday live and work, such as asteroids, the Moon, and Mars, there is strong scientific interest in each of these destinations. There is also increasing private sector interest, either in offering new services or potential exploitation of space-based resources. With several nations working on capabilities to send humans beyond low-Earth orbit (LEO) in the next decade, human exploration of the solar system will proceed. All of these factors strengthen the importance of coordination during mission formulation or planning activities to create opportunities to realize a wider set of benefits to all stakeholders.

Human exploration of the solar system will proceed in a step-wise manner, extending proven capabilities to achieve more complex goals while enabling new discoveries with each step. Human presence beyond LEO enables new opportunities for realizing space exploration goals and objectives. This applies not only to the presence of crew but also to space-based infrastructure emplaced to enable human exploration objectives to be met. Infrastructure such as habitation, communication and servicing systems can support the needs of many prospective missions. Agencies now participating in ISECG have established significant human spaceflight capabilities for reaching and using LEO. They are conducting research onboard the International Space Station and testing systems needed for a future Chinese space station. They are also sending robotic probes into the solar system. Nations now look beyond LEO in order to keep advancing strategic human spaceflight capabilities and delivering the benefits to citizens on Earth (Ref 1). Within ISECG, interested agencies are advancing future mission concepts which show promise for returning an expanded set of benefits when both human and robotic capabilities are brought to bear. Concepts such as human-assisted sample return demonstrate how increased benefit can be derived from human-robotic mission partnership.

The widespread recognition of the updated Global Exploration Roadmap (GER), released in August 2013 (Ref 2), 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 utility of these planned missions and create opportunities to realize additional missions. Concepts can be elaborated and compared within ISECG. Results from these collaborative activities may be used by individual mission owners (public and private) during mission formulation and planning work to achieve a higher return for investments. This paper describes relevant work under way within ISECG to promote this objective.

CONTINUING WORK ON A HUMAN SPACE EXPLORATION ROADMAP

The GER describes 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. As shown in figure 1, the Global Exploration Roadmap emphasizes the near-term initiatives in implementing the common international strategy, namely: 1) fully utilizing the ISS, 2) continuing efforts to expand on synergies 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. Each of these near-term initiatives is a priority for participating space agencies at the current time. The effort to fully utilize the ISS is pursued by ISS partner agencies and not a focus of ISECG, per se. By lowering the costs of doing research on the ISS and simplifying the process for accessing the ISS, the ISS partners are already seeing increasing demand for the unique laboratory in LEO. ISS partners are also using ISS to prepare for future exploration missions (Ref 3).

Within ISECG, an expanded set of participating space agencies continues the human spaceflight road-mapping effort. China is a recent addition to the group of participants. Agencies participating in ISECG are focusing on initiatives to expand the human robotic partnership and elaborate definition of the human missions beyond LEO, as highlighted in Figure 1. The intention is to promote partnerships, as well as advance and expand on definition of near-term mission concepts and scenarios to support the government decisions to realize space exploration

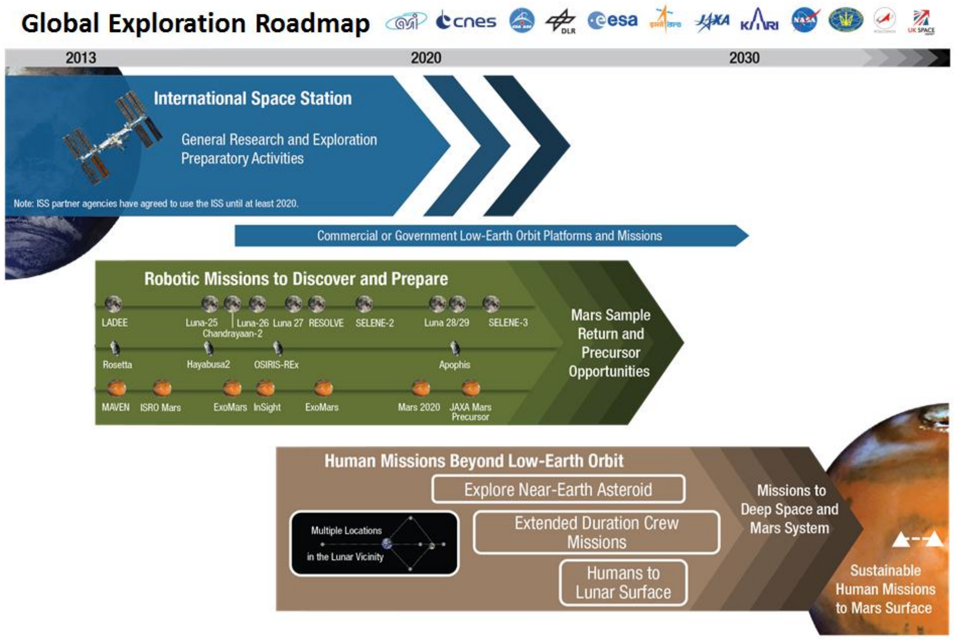

Figure 1: The Global Exploration Roadmap highlights near term exploration priorities

missions and preparatory activities. The addition of China as a participant in this work may create near-term collaboration opportunities on Chinese robotic missions or long-term potential enhancements of the global exploration endeavour. This paper describes efforts to expand the human robotic partnership. The work of ISECG to advance definition of the human missions beyond LEO is described in *The Exploration Mission Themes in the Global Exploration Roadmap*, B. Hufenbach et.al (Ref 4).

EXPANDING THE HUMAN-ROBOTIC PARTNERSHIP

A number of robotic missions to future human exploration destinations are planned by space agencies participating in the ISECG (see Figure 2). In addition, several privately funded efforts are advancing concepts for missions beyond LEO. On the human side, NASA expects to conduct the first crewed mission test of its Space Launch System and Orion vehicles in 2021. Roscosmos is also advancing systems necessary to send humans beyond LEO. Several agencies, including NASA, are advancing concepts for another fundamental human exploration capability, deep space habitation. All of these capabilities and missions present opportunities for coordination which increase the value delivered to stakeholders.

Within this context, the Global Exploration Roadmap describes several initiatives which can benefit from increased human/robotic mission partnership. A significant effort within ISECG is being placed on advancing two of these concepts: human-assisted sample return and a lunar polar volatile strategy. Each of these is further described in this section. A third mission concept is elaborated in the roadmap, namely that of low latency, high bandwidth tele-operation of surface assets by crew in the vicinity of the planetary surface. Several activities to further understand the potential of tele-operation concepts are in work by several individual space agencies (either individually or in partnership), and not a focus of ISECG this year.

Agencies participating in ISECG have established strategic shared principles to inform mission scenario development. Each of the driving principles is a necessary consideration of a sustainable human exploration effort. The principles reflect what is important to key agency political stakeholders. For example, affordability constraints dictate that the value delivered by each exploration mission be significant and as far reaching as possible. These principles also guide the advancement of human-robotic mission concepts described in this paper. ISECG has been mindful of the considerations

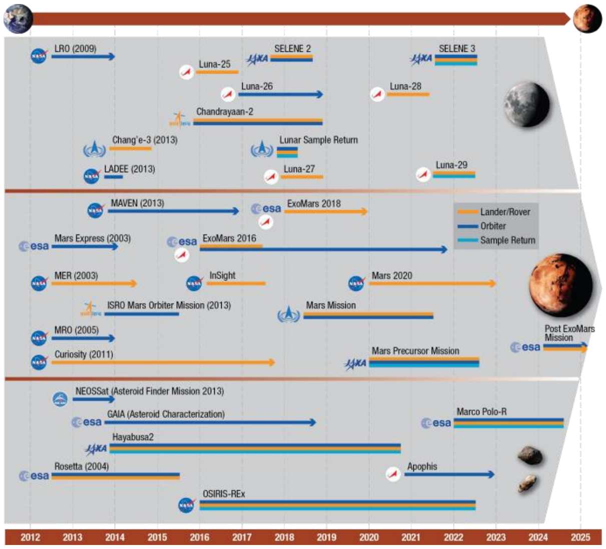

Figure 2: Robotic missions: On-going and planned robotic missions. Most missions feature international partnerships with technical and scientific contributions from other agencies.

of each community while looking for initiatives which have the potential of creating a meaningful step in expanding the human robotic mission partnership (see Figure 3). The mission concepts under consideration will be evaluated against criteria such as those embodied in the driving principles. Ensuring the sustainability of space exploration is the overwhelming driver to pursuing initiatives which expand the human robotic exploration partnership.

Strategic Principles	Application to Human Robotic Mission Concepts
Affordability	Focus on robotic missions in the formulation phase, prior to selection or finalization of mission plans and payload.
Exploration Value	Respect robotic mission planning processes which are well established.
International Partnerships	Lower the barriers which drive costs of robotic missions to enable more agencies to realize missions.
Capability Evolution	Use early missions to emplace assets to serve future missions.
Human/Robotic Partnership	Identify technologies which can be advanced to benefit both future human and robotic missions.

Figure 3: Strategic principles applied to human/robotic mission concepts.

Human Assisted Sample Return

Samples of material from celestial bodies collected in context and returned to Earth for detailed study is one of the highest priorities of the planetary science community. Samples of lunar surface material were collected during the Apollo and Soviet Luna missions. A small sample from the asteroid Itokawa was returned in 2010 by the Japanese mission Hayabusa. Additional robotic missions to collect and return samples from asteroids and the Moon are in advanced stage of readiness. Hayabusa2 will launch in late 2014 to study and return a sample from the asteroid 1999 JU3, while NASA's OSIRIS-REx spacecraft will launch in 2016 and return a sample of the asteroid Bennu in 2023. NASA is formulating the Asteroid Redirect Mission, which promises to return a large amount of sample from an asteroid (target to be identified) which has been relocated to cis-lunar space and explored by crew in Orion. Lunar sample return missions are planned by Roscosmos and China. Other agencies are studying possible future missions demonstrating the importance of sample return to the science community. Of course, the 'holy grail' of sample return missions is arguably Mars sample return. Acquiring a sample of Mars to further advance our understanding of whether life ever existed on Mars has been a priority for the Mars science community for decades.

Human-assisted sample return concepts take advantage of human support capabilities and crew presence to return the samples in a manner that reduces cost and complexity of robotic missions. Samples are returned to the lunar vicinity robotically and collected by crew who are there to advance human space exploration goals and objectives (not solely for the purpose of collecting the samples). The Human-Robotic Opportunities Workshop, conducted in March 2013 (Ref 5), examined various mission concepts and concluded that human-assisted sample return would enhance the value of sample return missions in several ways, listed below:

- Increased science return with a larger and more diverse set of samples;
- Reduced complexity of robotic mission, transferring sample handling responsibilities to the crew and Earth re-entry capabilities to the crew system;
- Improved mission robustness and reliability due to having a human in the loop;
- Better opportunities for public engagement due to astronaut involvement;
- Broader opportunities for international cooperation.

Workshop participants assumed that humans would be in cis-lunar space for their own reasons, not purely for the purpose of collecting samples. This assumption enables a reasonable cost comparison between a human-assisted approach and a completely robotic mission approach. Several agencies are advancing concepts for human-assisted lunar and Mars sample return and sharing this work within ISECG. It is necessary to demonstrate the added value provided by such an approach over a purely robotic sample return mission. ISECG will contrast and compare the various mission concepts and look for synergies which could lead to preferred concepts and opportunities for collaboration to realize the possible missions.

In a study led by the Jet Propulsion Laboratory, NASA is examining concepts for human-assisted Mars sample return. The study builds on the robotic mission concepts favoured by the international community and reflected in iMars report (Ref 6). The iMars concept for Mars Sample Return (MSR) assumes four main elements, each representing a significant investment. First, a robotic mission to the surface of Mars obtains and caches sample for later return to Earth. Next, 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 NASA/JPL human-assisted sample return study assumes the success of the Mars 2020 mission to collect and cache samples of interest to the science community. Initial study findings were briefed at the NASA Community Workshop on the Global Exploration Roadmap, held in April 2014 (Ref 7). Updates are shared within ISECG to advance the development of mission concepts for human-assisted sample return.

Planetary protection guidelines have been established by international experts. These have been taken into account by NASA in the publication of policy requirements and guidelines applicable to its robotic or human exploration missions. These policy statements are intended to ensure NASA missions conform to international expectations regarding limiting contamination of planetary surfaces by spacecraft sent from Earth and preventing adverse changes in the environment of Earth by extra-terrestrial matter. These policy requirements have a large cost impact on robotic missions to Mars, especially those planning to return a sample from Mars. For example, techniques are needed to ensure that the probability of a single Martian particle reaching Earth can be reduced below acceptable limits. Meeting this requirement is known as ‘Breaking the chain’ of contact with Mars and contributes to the complexity of MSR. The NASA/JPL study includes options for using the crew to ‘break the chain’ or contribute to the confidence that it is successfully broken before a sample leaves the vicinity of Mars.

<u>Lunar Volatiles as a Means to Advance ISRU Capabilities</u>

Use of local resources present on the Moon, asteroids and Mars could limit the cost and complexity of bringing all the needed supplies from Earth and contribute to the long-term sustainability of human space exploration. Much remains to be done before specific exploration architectures which rely on the use of local resources can be chosen. Detailed study of lunar polar volatiles provides the near-term opportunity to answer some of the key questions needed for future exploration scenarios. Operational use of resources obtained from the Moon or asteroids is not envisioned in the ISECG mission scenario because they are not needed to support the chosen scenario. However, the use of resources on Mars is essential and the study of lunar polar volatiles can provide information and advance technologies usable in the Mars environment.

Mars resource utilization has primarily focused on providing oxygen to the crew and possibly fuel for ascent propellant from the Mars surface to orbit, by processing carbon dioxide collected from the Mars atmosphere. While the Moon does not have an atmosphere, higher levels of hydrogen have been measured in the polar region. Neither the exact concentration of the volatiles, nor the precise distribution is known. Technologies and techniques used for prospecting and volatile processing on the Moon have a direct application to Mars.

For the science community, understanding how volatile elements and compounds are distributed, transported and sequestered in near-surface environments is one of the most important questions (Ref 8). There are other science questions such as what was the role of bombardment?

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. ISECG is working on a possible strategy for international coordination of efforts to enable these key questions to be answered. 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. Their interests will be understood and given a voice in the effort.

Four key elements of a potential strategy, listed below, are under consideration.

1. Common polar region
   By study of all the recent information collected about the Moon in recent years, is there a region of interest most likely to enable answers to questions of interest by multiple stakeholders?
2. Common infrastructure
   Identify opportunities for common infrastructure to lower the cost of accomplishing any single mission, thereby opening opportunities for more players. Consider infrastructure such as communication relay, secondary payloads, navigation aids or surface utilities.
3. Available hardware assets
   Identify available flight hardware which can be reused or adapted for individual mission needs. Hardware such as rovers, sensors, cameras, power sources and drilling equipment are candidates.
4. Data sharing
   What level of data should be shared in such a collaborative framework?

<u>Tele-presence</u>

Tele-presence can be defined as tele-operation of a robotic asset on a planetary surface by a person who is relatively close to the planetary surface, perhaps orbiting in a spacecraft or positioned at a suitable Lagrange point. Potential tasks include those characterized by high-speed mobility, short mission durations, focused or dexterous tasks with short-time decision-making, reduced autonomy or redundancy on the surface asset as well as contingency modes/failure analysis through crew interaction. Application of this capability to lunar robotic missions is under study (Ref 9). It may be that Mars exploration provides the best opportunity to realize the benefits of these capabilities because early human missions to Mars may be missions where the crew does not land on the surface of Mars but remains in Martian orbit or the vicinity of Phobos or Deimos.

While not a specific focus of collaborative work in ISECG in 2014, work is going on around the world to understand the potential for low-latency, high bandwidth tele-operation of surface assets from a crew in the vicinity of the planetary surface. One example is the ESA METERON experiment which is currently underway onboard the ISS. Astronauts have controlled robotic systems located on the Earth from the ISS. See figures 4 and 5. ESA plans to launch an exo-skeleton control device to the ISS in 2016 and plans a series of experiments to ascertain the most promising latency/data rate combinations which make tele-presence an interesting control mode. The Canadian Space Agency also used the ISS for a series of tele-presence demonstrations in 2009. The Avatar series of experiments made use of the ISS crew to control robotic devices on the ground in Canada to test the performance of remotely controlled devices by a crew in orbit (Ref 10).

Figure 4: ESA astronaut Alexander Gerst steers ESA's Eurobot rover from the ISS.

Figure 5: The ESA Eurobot rover being controlled by Alexander Gerst from the ISS.

JAXA is studying a mission to promote lunar far side exploration and sample return. The mission will demonstrate technologies for space exploration such as autonomous traverse over long distances, drilling and ISRU as well as capture a sample and return it to Earth. Astronauts in the lunar vicinity can oversee and control the lunar robotic assets to improve possibility of mission success. Infrastructure in the lunar vicinity, such as EML-2, would also provide communication relay between the far side robotic rover and equipment and ground controllers in Japan.

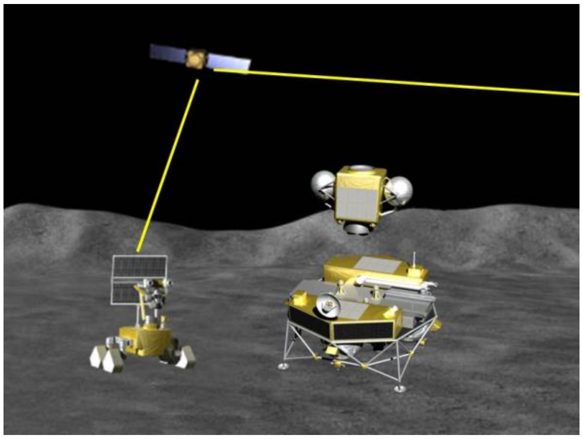

Figure 6: Image from JAXA study of far side lunar robotic exploration supported by humans in the lunar vicinity.

At the same time, agencies are seeking to leverage synergies with technology developments for terrestrial applications for the benefit of both. As an example, Germany has initiated a research alliance on the robotic exploration of extreme environments (ROBEX), where research and engineering communities for lunar robotics and deep sea exploration jointly discuss their requirements and challenges (Ref. 11). See figures 7 and 8. This allows both the transfer of aerospace expertise into the challenging efforts in deep sea robotics, but also to learn from the human-robotic partnership in this terrestrial exploration efforts where a direct presence of humans is impossible and to exploit its activities and experience for the acceleration of space technology and operational developments. Dedicated topical teams are discussing synergies in fields such as mobility, navigation, manipulation, autonomous operations, and many more.

Figure 7: Deep sea ROBEX robot concept

Figure 8: The German research alliance ROBEX aims at exploiting synergies between deep sea exploration and lunar robotics at all stages of the process of technology developments and system operations (image credits: NEPTUNE/DLR).

BUILDING STAKEHOLDER SUPPORT

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. As chair of the ISECG, the head of the Canadian Space Agency shared with the representatives of over 31 nations the progress being made by ISECG and the impact of the updated Global Exploration Roadmap. The meeting outcome, captured in a *Forum Summary* (Ref 12), notes several important government priorities. The value of space exploration is recognized 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. Each type of mission contributes knowledge and technology which expands the set of exploration objectives which can be achieved. This final point reflects the high priority placed on the work by ISECG to look for ways to strengthen human robotic mission collaboration. It also creates a positive outlook for cooperation proposals which may result from this work.

The next meeting of the ISEF will be hosted in Japan. 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. While the ISEF is not a governance body, it serves a very positive role in reinforcing the importance of international collaboration in exploration and demonstrating that importance of involving many nations in the effort.

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. In addition, efforts to understand the origin and promise of lunar polar volatiles will bring information of interest to scientists and human mission planners. With the progress made by NASA on the Orion and Space Launch System, humans will be working in the lunar vicinity starting as early as 2021. The presence of humans in space opens up new and innovative applications, something consistently demonstrated throughout the history of human spaceflight.

The work of agencies to advance innovative mission concepts like human-assisted sample return and tele-presence is expected to lead to new international collaboration and cooperation opportunities which will be reflected in the next update of the Global Exploration Roadmap. As a living document, the roadmap shows planned human and robotic exploration missions and provides the context for international evaluation of concepts and scenarios which expand human and robotic exploration. ISECG continues to be an effective forum for advancing concepts and scenarios in a collaborative manner, creating a foundation for future partnerships.

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