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AN INTERNATIONAL APPROACH TO THE COORDINATION OF TECHNOLOGY DEVELOPMENT EFFORTS ENABLING THE GLOBAL EXPLORATION ROADMAP

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Abstract

The International Space Exploration Coordination Group (ISECG) is a voluntary, non-binding coordination forum of 26 space agencies. Each step in expanding human presence beyond low Earth orbit relies on the readiness of new capabilities and technologies. As individual agencies may not have the resources to develop all these critical capabilities, appropriately leveraging global investments in technology development and demonstration is important.

Space agencies participating in ISECG have identified a list of critical technologies that need to be developed or matured, as relating to the missions shown in the 2018 Global Exploration Roadmap (GER) architecture, and the 2020 lunar focused GER Supplement. These technologies can be considered "mission-pull" from the GER point of view, even if the performance characteristics are to be seen as targets and not as mission defined requirements. These technology needs can be mapped to corresponding agency technology development activities; subsequently global technology gaps can be assessed.

The work presented in this document is maintained by the ISECG/Technology Working Group (TWG) and details the activities of critical gap identification and coordination, mapping of those gaps to agency technology development activities, identification of gaps in technology developments to advance the GER, and topic-focused gap assessment teams.

Keywords: Critical Technologies, Gap Assessment, Technology Development, Global Exploration, International Collaboration.

Acronyms/Abbreviations

International Space Station (ISS)
International Space Exploration Coordination Group (ISECG)
Global Exploration Roadmap (GER)
ISECG Technology Working Group (TWG)
GER Technology Development Mapping (GTDM)
Gap Assessment Teams (GAT)
Technology Readiness Level (TRL)
In-Situ Research Utilisation (ISRU)

1. Introduction

Space exploration is propelled by the desire to understand humanity's origins, future destinations, and potential resources, in addition to pursuing economic prosperity and higher industrial capability. To engage the community support, useful tools have been found in educational and inspirational initiatives that, like the Apollo Program, captivate the imagination of the public and familiarizes technological development. However, inspiration must be balanced by the commitment to deliver benefits to the society, be it at a medium or long timespan.

To achieve such endeavours, space programs are intrinsically associated to technological advances and increasing challenges while pushing towards the continuity of human spaceflight and the utilisation of space resources, be it on Earth's orbit or beyond. Humanity's home at the ISS has served as a springboard to more recent programs that aspire to achieve sustained living and working

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on the surface and orbit of the Moon as a technological foundation to future sustainable human missions on Mars.

Regardless of the competitiveness for space exploration found between national space programs and emerging private initiatives, there is a culture of cooperation inherent to space exploration. This is mostly due to the high level of required funding, not sustainable by one single national agency. The experience of the International Space Station is a particularly good proof of the results that can be achieved by a wide international cooperation. The ISECG is an even wider community of space agencies than the ISS partnership and could in principle foster a truly international cooperation for the next steps of human exploration. This would imply to share the goal of exploration and to optimize the development of the required building blocks, also in terms of the needed critical technologies.

1.1. ISECG

The ISECG was initially established by 14 space agencies, as a response to The Global Exploration Strategy: The Framework for Coordination, released in 2007 [1]. A key finding of this framework document was the need to establish a voluntary, non-binding forum of space agencies to coordinate and exchange information regarding interests, plans and activities in space exploration. This coordination mechanism is the ISECG, a collective effort amongst individual exploration programs, that envisions cooperation to strengthen individual capabilities through international collaboration.

The Framework presented an initial vision for globally coordinated human and robotic space exploration to the Moon, near-Earth asteroids, and Mars; while the creation of the ISECG reaffirmed the interest of participating space agencies. The participating entities began a series of discussions on global interests in space exploration and developed a common set of key space exploration themes guided by base principles: open and inclusive; flexible and evolutionary; effective; supportive of mutual interests. To guide technological efforts of individual space agencies, the ISECG developed the Global Exploration Roadmap (GER).

The GER [2] reflects consensus about the importance of the Moon on the pathway to Mars and adds refinements in each step along this path as agencies continue to make individual and collective progress. The roadmap demonstrates how capabilities under development or study around the world could enable a sustainable future of human and robotic space exploration.

While not committing individual agencies to specific steps and activities, the GER serves as a reference for generating innovative ideas and solutions to address the challenges ahead together. The GER represents a blueprint of next steps for the current and next generation of explorers. Governments, the private sector, and academia will determine investments and partnerships that can translate this blueprint into tangible progress extending human presence into deep space, with the associated socio-economic benefits.

There are currently 26 agencies participating in ISECG, as shown in figure 1. When GER 2018 was released the number of participating agencies was 15, thus 11 joined in the last three years, showing the growing interest of space agencies toward ISECG.

1.2. Technology Working Group

Recognizing the strategic nature of technology investments for agencies, the TWG was formed within the ISECG, to advocate coordination and collaboration in technology development efforts of individual ISECG space agencies in support of their interests to enable contributions to future international missions like those within the GER. The TWG has currently 14 participating space agencies.

TWG activities aim to provide linkage between capabilities/elements identified in the ISECG mission scenario and its critical technologies required, including the associated target performance characteristics.

Amongst the activities of the TWG is the mapping of agency plans against reference capabilities required for implementation of GER, including an investment gap analysis. The goals are:

- Perform technology gap assessments in key areas related to future exploration and the GER

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architecture and identify opportunities for collaborative technology development (with focus on critical technologies).

- Identify opportunities for collaborative technology demonstrators to be implemented on ground (e.g. analogue activity) or in space with focus on critical technologies.
- Identify potential partnership opportunities in technology development efforts, while maintaining an updated GER architecture mapping.

The purpose of this paper is to share ISECG's approach to advance the coordination of technology development efforts through the TWG activities of critical gap identification and coordination, mapping of those gaps to agency technology development activities, identification of gaps in technology developments to advance the GER, and topic-focused gap assessment teams.

2. GER Technology Development Mapping - GTDM

The TWG categorises technology development inputs of participating space agencies by technology areas and maps them to the elements and capabilities identified in the GER mission scenario.

The GER scenario (figure 2 and 3) advances with time and is updated periodically, as can be seen from recent and future endeavours planned by ISECG participating agencies. TWG activities are currently built on the recent GER version, published in 2018 [2], and on the 2020 lunar surface dedicated Supplement [3]. The Supplement describes emerging national and commercial capabilities to enable lunar initiatives that will serve as preparation for further activities on the Moon, and for future missions to Mars.

ISECG space agencies have identified a list of critical technologies [4] related to the missions shown in the 2018 GER that are currently not available or that need to be developed or matured. These technologies are considered "mission-pulls" in the grand scheme of the GER roadmap and can be mapped to corresponding agency technology development activities. It is building on a portfolio list of enabling critical technologies resulting from a human deep space exploration architecture analysis conducted by NASA and published in 2019 [5]. This mapping allows a global technology gap assessment.

NASA taxonomy is used as the basis for mapping GER critical technology needs, against the technology development efforts of member agencies. The NASA taxonomy framework serves as the reference for cross-mapping of capability areas to the relevant GER critical technology needs. With the recent update of the NASA taxonomy framework, the TWG is currently transitioning from the use of the Technology Area Breakdown Structure (TABS, 2015) to the new NASA Taxonomy 2020 framework.

The GER technology development mapping effort enables TWG members, enabling TWG members to view all technology development efforts across member agencies, and effectively identifying areas of potential collaboration, while targeting specific GER critical technology gaps.

3. GTDM High-Level Analysis

The GTDM High-Level Analysis is an on-going effort to close critical gaps by highlighting areas where further development is necessary to successfully meet our GER mission scenario and where collaboration opportunities among agencies may arise.

The objective of this high-level analysis is to understand which agencies are working on what critical technologies and to what degree to determine if there are any gaps in current technology developments to support the GER exploration missions and if the gaps are being closed with the current investments. In addition, the high-level analysis can point out opportunities for collaboration amongst the agencies. Finally, the analysis summarizes any issues and/or concerns with the approach to gap closure ranging from insufficient investments to no agencies investing to close a specific gap, for example.

To perform the high-level analysis, the TWG grouped the critical technologies into six themes seen in detail on tables 1 to 6, that explore the remaining critical technologies by reference number on the GER, theme and mission application (lunar and Mars, vicinity and surface). Main themes are as outlined below in subsections 3.1 to 3.6.

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3.1. Propulsion, Landing, Return:

Cryogenic propulsion systems, nuclear thermal and nuclear electric propulsion, precision landing, Mars entry, descent, and landing, and zero boil off. 6 agencies are currently supporting technology development in this area.

3.2. Autonomous Systems

Autonomous vehicle systems management, automated rendezvous and docking, in-space timing and navigation, crew autonomy, and mission control autonomation. 7 agencies are currently supporting technology investments in this area.

3.3. Life Support

Closed-loop life support systems, enhanced reliability life support systems, in-flight environmental monitoring, fire prevention, detection, and suppression, and space radiation protection. 8 agencies are currently supporting technology investments in this area.

3.4. Crew Health & Performance

Long duration spaceflight medical care and behavioural health and performance, microgravity biomedical countermeasures, human factors and habitability, and long duration storage for perishable goods. 9 agencies are currently supporting technology investments in this area.

3.5. Infrastructure & Support systems

Areas of communication (high data rate forward link, proximity, and return link comms), power (high strength/stiffness deployable solar arrays, fission power, regenerative fuel cells, low temperature and long-life batteries), and infrastructure (in-situ resource utilisation, dust mitigation, inflatable structures & materials, low temperature mechanism, and thermal control) technology development. 8 agencies are currently supporting technology investments in this area.

3.6. EVA/Mobility/Robotics

Telerobotic control, working side-by-side with suited crew, Extra Vehicular Activity suits, and surface mobility systems. 11 agencies are currently supporting technology investments in this area.

4. Gap Assessment Teams - GAT

Each step in expanding the human presence beyond Low-Earth Orbit (LEO) relies on the readiness of new capabilities and technologies. The TWG identified critical technologies related to the missions envisioned in the GER, which are currently not available or need to be developed or matured.

The GATs address the identified technology needs, refining the high-level analysis in additional detail. The GATs are focused assessments in specific technology area that feed back information to complement the GTDM and high-level analysis. This has been the method behind of the past 5 GATs, as shown on the subsection 4.1 to 4.5. The key findings of the two most recent works are presented in more detail on subsections 4.4 and 4.5.

The assessment provides valuable information to individual space agencies:

- Highlight and substantiate existing gaps.
- Detailed analysis will inform space agencies and support long-term planning.
- Create international dialogue among experts.
- Support agency decisions to increase investment in exploration technologies.
- Identify collaboration opportunities.

4.1. LOx/Methane propulsion GAT (2016)

Liquid Oxygen/Methane propulsion technologies can make use of in-situ propellant production, lead to improved performance, and leverage fluid commonality. Technology gaps that need to be addressed include throttleable engines, thrusters with integrated cryogenic feed systems, long-duration reliable cryogenic refriger-ation systems, and high-performance pressurization systems that improve storage density and reduce mass [6].

4.2. Dust mitigation GAT (2016)

Dust mitigation technologies are a key enabling factor to perform extended duration lunar surface missions. While viable technology solutions have been identified by experts, there is a need for the maturation of related technologies to support both lunar and Mars missions. No single technology completely solves the challenges of dust, but rather

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a suite of technologies will be required to address them [7].

4.3. Telerobotics GAT (2018)

Telerobotic operations with time delay can make human-in-the-loop commanding and monitoring of robots at remote distances less effective. For safety and efficiency with time delays greater than five seconds, it is recommended that robots be operated as autonomously as possible. Terrestrial applications in this area are well advanced but on-orbit applications need to be matured [8].

4.4. Autonomy GAT (2020)

The Autonomy Gap Assessment team was chartered to assess the state of the art for Autonomy area technologies, systems, and capabilities, and to define the remaining work (gaps) that will need to be performed and completed to finally achieve the desired end-goals for Autonomy incorporation into human lunar and Mars exploration.

Key findings of the Autonomy GAT Report content [9] are detailed below from subsection 4.4.1 to 4.4.7:

4.4.1. Vehicle Autonomy

- In the field of autonomy in support of crew decision-making, perception and reasoning are the areas requiring more work.
- In the field of autonomy without humans in the loop, some systems (e.g., Timeliner) have been successfully deployed on the ISS and could be expanded to future Moon and Mars exploration activities.
- While investment in research activities from different space agencies cannot be neglected, the path for autonomous systems to be deployed in vehicles is extraordinarily complex, even more so for crewed vehicles. As a result, most of these systems still require further advancements in Technology Readiness Level (TRL).
- A machine-learning boom in Earth applications might have positive effects in potentially every autonomy function described in the report (e.g., knowledge modelling, motion planning, etc.).

4.4.2. Crew Autonomy

- Mission control capabilities must be enhanced. Ground systems currently used to pre-plan almost every task to be executed on board must evolve to support operations concept and mission scenarios that will migrate from ground-based controllers to autonomous control at the destination point, where only long-term strategic planning will be ground-based.
- The gap assessment revealed critical gaps mostly concentrated in the area of perception and situational awareness. It is currently an issue to infer temporally contextualized knowledge regarding the state of the user (based on heterogeneous sensor readings and previously inferred knowledge). This appears to be the most critical gap, for the lack of technologies and competences also on terrestrial applications.
- A criticality also can be envisaged on what concern the V&V of the technologies embedded in the intelligent ambient, as well as the need of providing understandable and transparent behaviour (explainable AI).

4.4.3. Crew Health & Performance

- Substantial investment in Research and Development (R&D) is ongoing for in-situ bio-analysis tools, with further fine-tuning required. Further R&D into systems supporting health monitoring, diagnosis support, resource planning and robotically assisted surgery are some of the key gaps identified in this report.
- Certain crew autonomy systems will benefit from advanced developments in terrestrial applications, spinning-in technologies matured through application in hospitals, other medical facilities and other industries.

4.4.4. Food Production

- Larger scale terrestrial demonstrations for autonomous food production and demonstrations in LEO are progressing in the area of plant growth and plant habitats, but currently cannot be scaled up to a level to demonstrate sustainable, autonomous

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production to provide food and nutrition for the crew during operations beyond LEO.
- Critical gaps must be addressed in the areas of sensing, knowledge and intent conveyance and understanding, anomaly and fault detection, diagnosis and prognosis, fault response and actuation to enable food production beyond LEO.

4.4.5. Crew safety and Intervention

- Due to the complexities associated with automated decision support systems and autonomous operations, it is vital to provide information to the crew in a comprehensive and intuitive format to increase crew confidence in system alerts and actions.
- Technology maturation/demonstration in operational environments is taking place and will help to understand and improve the balance between requirements for autonomous intervention and manual intervention to ensure crew safety.
- Additional research is required to ensure transparency in plans and decisions made and carried out by automated/autonomous systems. Critical gaps must be addressed in knowledge and intent conveyance and understanding, diagnosis and prognosis, fault response and actuation in order to ensure the crew is not put into an unsafe condition or that the crew does not unknowingly create an unsafe condition.

4.4.6. Robotic Caretakers

- For the cislunar environment, where the time delay is fairly short, robots may be teleoperated from Earth. As missions venture deeper into the solar system and time delays from Earth increase, robotic caretaker systems will need to be able to plan tasks automatically with limited crew inputs. These systems also will need to operate in the presence of human crew and as team members with human crew.
- Critical gaps must be addressed in sensing, state estimation and monitoring, hazard assessment, diagnosis and prognosis, fault response and actuation in order to enable crew and mission autonomy beyond LEO.

4.4.7. Stowage Management

- Demonstration and test of cargo and inventory management systems onboard ISS are paving the way for maturation of a capability for robust capabilities to support crew and mission autonomy beyond LEO.
- Critical gaps in sensing, state estimation, knowledge and intent conveyance and understanding, activity and resource planning, diagnosis and prognosis must be addressed to complete the technology maturation process.

4.5. In-Situ Research Utilisation GAT (2021)

As the name implies, the ISRU Gap Assessment team was chartered to assess the state of the art for ISRU technologies, systems, and capabilities, and to define the remaining work (gaps) that will need to be performed and completed to finally achieve the desired end-goals for ISRU incorporation into human Moon and Mars exploration. To perform this task, the team utilized the highest priority/impact ISRU products and applications, the ISRU functional breakdowns, and information gathered in the ISRU-related technology portfolio assessment per agency/country, to provide decision makers and developers an understanding of the remaining work that needs to be addressed in future efforts.

Because there are no firm requirements for ISRU products and systems, the gap assessment performed is meant to provide general information at the capability-level versus highly specific parameters that would be needed for a technology-level gap assessment.

Ultimately, the ISRU Gap Assessment was intended to inform agency decisions when considering investments in specific exploration technologies, while identifying potential collaboration opportunities. The final report was also intended to provide information to industry and academia on the current state of ISRU, areas of importance for future missions, and knowledge on development activities, facilities, and gaps that could help direct and focus future investments. The report provides a broad and comprehensive assessment of ISRU. Starting with defining the subject of ISRU, the report provides a taxonomy of the main ISRU areas (Consumable Production,

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Construction, and Manufacturing with ISRU-derived Feedstocks), and a functional flow diagram to allow readers to understand the content and interconnectivity of the functions and technologies. The report provides information on potential resources, products, and applications, strategic knowledge gaps, and how ISRU can be incorporated into mission phases for human exploration of the Moon and Mars. The report provides detailed assessments of recent development activities, available facilities, and simulants to support development, and areas of activity and interest for each space agency. The report ends with an assessment of the gaps remaining, challenges, missions to address the challenges and implement ISRU, discussions on partnerships, public-public and public-private partnerships, private investment, policy and regulatory challenges, and key findings and recommendations.

Key findings of the ISRU GAT Report [10] are detailed below from subsection 4.5.1 to 4.5.5:

4.5.1. Destination, Reconnaissance and Resource Assessment

- Almost everyone is working on instruments for geotechnical and mineral/ chemistry characterization.
- Strong interest in working on subsurface ice indirect and direct characterization.
- Strong interest in mobile resource exploration and autonomy.
- Several orbital and surface missions under development and planned.
- A focused and coordinated lunar resource assessment effort is needed to understand resource amounts/distribution and to better plan mining operations.
- Resource Acquisition, Isolation and Preparation.
- Requirements for resource acquisition, isolation, and preparation are linked to resource processing techniques.
- Strong interest in sample excavation of granular regolith and hard/icy regolith.
- Limited work on crushing, size sorting, and mineral beneficiation, most likely due to lack of firm requirements.
- Limited work on mobile excavation and delivery for larger scale systems at this time.

4.5.2. Resource Processing for Production of Mission Consumables

- The primary processes and products of interest are oxygen extracted from regolith and ice/water extracted from polar permanently shadowed regions.
- Even though several physical and chemical processes are well defined, these techniques require significant advancement before the incorporation into a mission demonstrator.
- Complementary and overlapping work on oxygen extraction and limited work on water extraction, mostly at demonstration scale.
- Water and carbon dioxide processing technologies for the Moon and Mars were mostly related to life support or terrestrial applications.

4.5.3. Resource Processing for Production of Manufacturing and Construction Feedstock

- Bulk or refined regolith will be the main constituent for construction, and manufacturing until more refined feedstock is available.
- Metal extraction processes requires generally also large amounts of power, necessary for both molten regolith and molten salt electrolysis technologies.
- Resource processing to produce plastics typically require complex and multi-step methods.
- As with oxygen extraction from regolith, complementary and overlapping work exists on metal extraction at the demonstration scale; most work is in the US and Europe.

4.5.4. Civil Engineering and Surface Construction.

- A significant radiation shielding needs to be realized for long, sustained human surface exploration activities.
- Specific manufacturing methods can be used as additive manufacturing that present relevant performance and a flexible approach but may limit the architectural opportunities.

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- While there is significant interest in terrestrial additive manufacturing / construction development, development for space applications have been limited and primarily under Earth-ambient conditions.
- Most of the current work is focused in US and Europe, with an emphasis currently on additive manufacturing approaches; Brick/slab making and sintering are also under development.

4.5.5. In Space Manufacturing

- Metals and polymers additive manufacturing techniques have been implemented or are being developed also for application in microgravity, on the ISS. Also, subtractive manufacturing systems are currently being developed for the ISS.
- Some relevant technics used for in Space Manufacturing for ISRU are using regolith with selective laser sintering method or stereolithography-based additive manufacturing.

5. CONCLUSION

The TWG is a coordination group across ISECG with the focus on understanding the state of technology development and investments across the ISECG community. The TWG has presented an overview of the work completed by the group, including the including the GER Critical Technologies, high-level analysis, and the Gap Assessment Teams. The GER technology mapping continues to be updated as agencies align their technology development efforts with future exploration endeavours. The TWG will complete and update to the critical technologies identified based on the GER Supplement. Once the critical technologies are updated, a high-level analysis will be completed to outline again where there are gaps in technology development and collaboration opportunities.

In addition, the TWG commissioned the Nuclear Power and Propulsion Gap Assessment Team, which was recently chartered and currently in-progress. The GAT was chartered to assess the state of the art for Nuclear Power and Propulsion technologies, systems, and capabilities, and to define the remaining work (gaps) that will need to be performed and completed to finally achieve the desired end-goals for Nuclear Power and Propulsion incorporation into human lunar and Mars exploration. The goal of the GAT is to publish a report by Summer of 2022. More information and recent re can be found on the ISECG webpage [11], in the Advanced Technology section [12].

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7. Figures

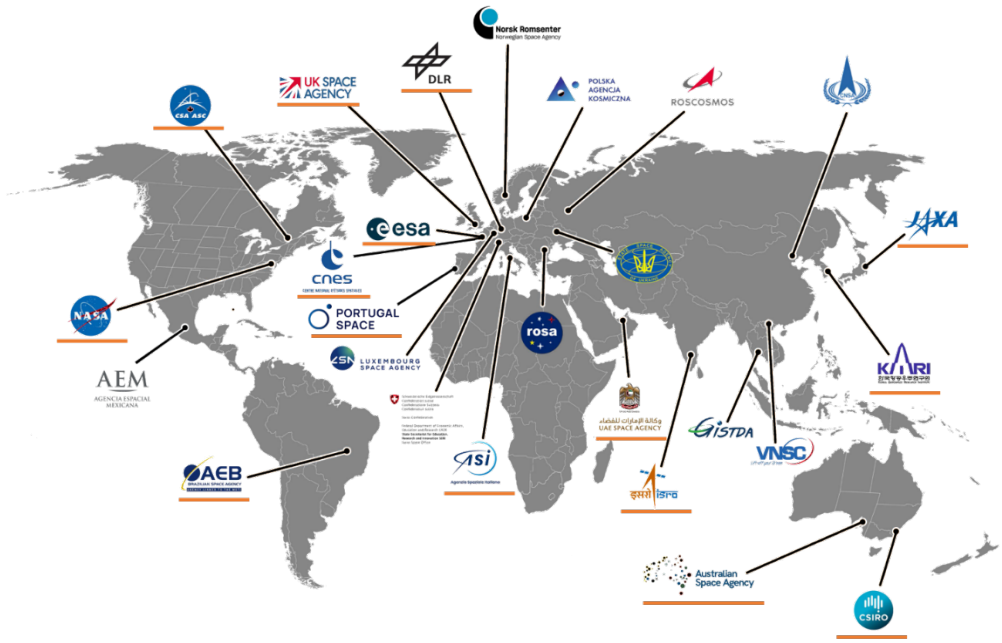

Figure 1. Map of ISECG participating space agencies: AEB, AEM, ASA, ASI, CNES, CNSA, CSA, CSIRO, DLR, ESA, GISTDA, ISRO, JAXA, KARI, LSA, NASA, NOSA, POLSA, PTS, ROSA, ROSCOSMOS, SSAU, SSO, UAE SA, UKSA, VNSA. Underlines (orange markings) highlight the TWG participating agencies.

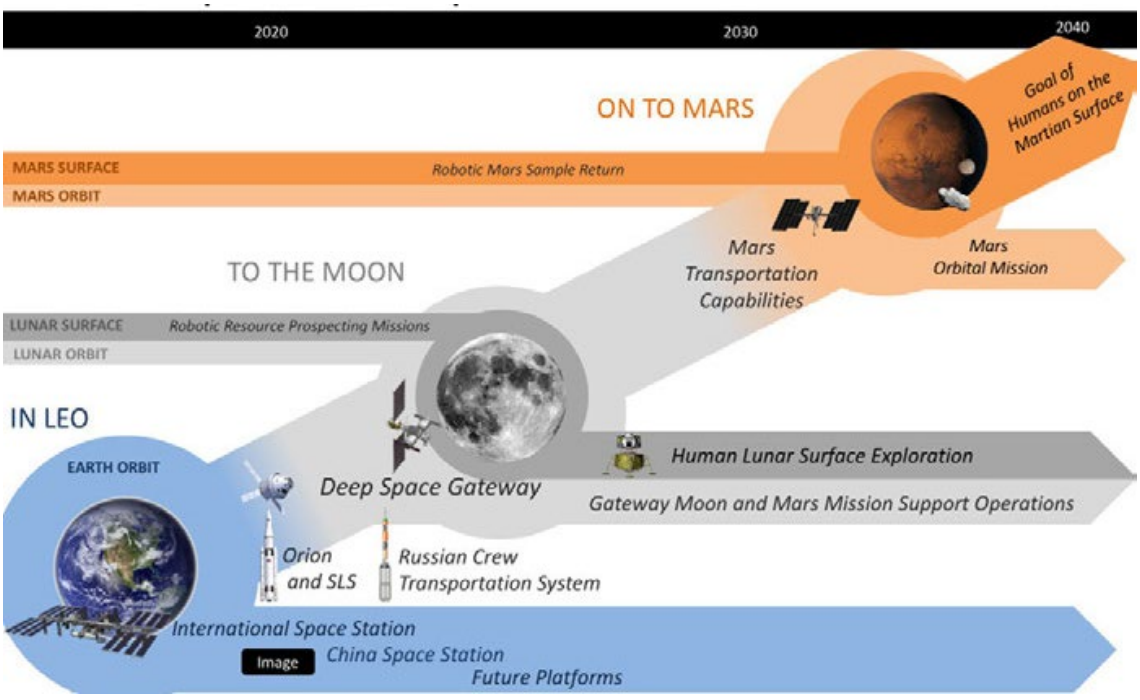

Figure 2. Global Exploration Roadmap Mission scenario

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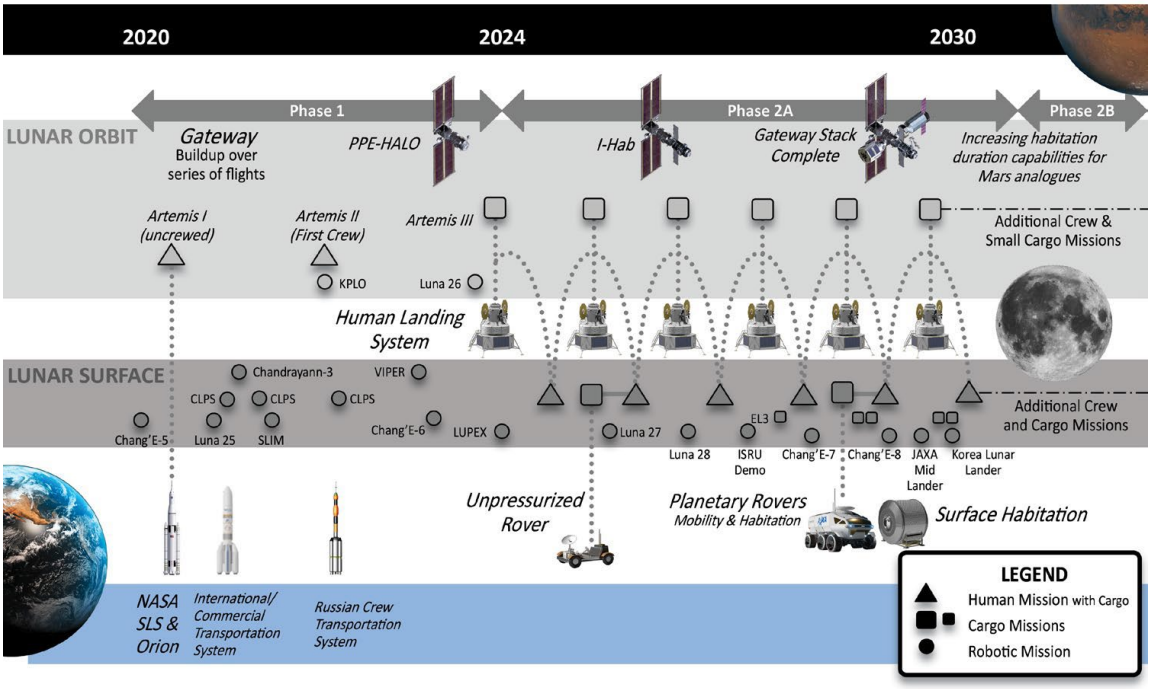

Figure 3. GER supplement August 2020 updated ISECG Lunar Surface Exploration Scenario

8. Tables

Table 1. Propulsion, Landing, Return

Ref. Number	GER Critical Technology (all)	Lunar Vicinity	Lunar Surface	Mars Vicinity	Mars Surface
GER-003	LOX/Liquid Methane Cryogenic Propulsion System		●	●	●
GER-006	Electric Propulsion & Power Processing			●	
GER-007	Nuclear Thermal Propulsion (NTP) Engine			●	
GER-009	In Space Cryogenic Liquid Acquisition	●			●
GER-014	Multi-MWe Nuclear Power for Electric Propulsion (NEP)			●	
GER-018	Precision Landing with Hazard Avoidance		●		●
GER-051	Mars Entry, Descent, and Landing (EDL) Technologies for Heavy Payloads				●
GER-062	In-Space Cryogenic Propellant Storage (Zero Boil Off LO2; Reduced/Zero Boil Off LH2)	●	●	●	●
GER-064	Robust Ablative Heat Shield (Beyond Lunar Return) - Thermal Protection System			●	●
Legend					
●	Technology development is Critical for currently baselined GER mission architecture				
●	Technology development is Critical Alternative within the GER mission trade space				

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Table 2. Crew Health & Performance

Ref. Number	GER Critical Technology (all)	Lunar Vicinity	Lunar Surface	Mars Vicinity	Mars Surface
GER-023	Crew Autonomy beyond LEO	●	●	●	●
GER-034	Long Duration Spaceflight Medical Care			●	●
GER-035	Long-Duration Spaceflight Behavioral Health and Performance			●	●
GER-036	Microgravity Biomedical Counter-Measures for Long Duration Spaceflight			●	●
GER-037	Microgravity Biomedical Counter-Measures: Optimized Exercise Equipment			●	●
GER-038	Deep Space Mission Human Factors and Habitability			●	●
GER-066	Long Duration Storage for Perishable Goods			●	●

Table 3. Life Support

Ref. Number	GER Critical Technology (all)	Lunar Vicinity	Lunar Surface	Mars Vicinity	Mars Surface
GER-029	Closed-Loop Life Support Systems			●	●
GER-030	Enhanced Reliability Life Support Systems	●	●	●	●
GER-039	In-Flight Environmental Monitoring	●	●	●	●
GER-040	Fire Prevention, Detection & Suppression (reduced pressure)	●	●	●	●
GER-041	Space Radiation Protection – Galactic Cosmic Rays (GCR)			●	●
GER-042	Space Radiation Protection – Solar Particle Events (SPE)	●		●	●

Table 4. Infrastructure & Support Systems

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Ref. Number	GER Critical Technology (all)	Lunar Vicinity	Lunar Surface	Mars Vicinity	Mars Surface
Communications					
GER-025	High Data Rate Forward Link (Flight) Communications			●	●
GER-026	High Rate, Adaptive, Internetworked Proximity Communications			●	●
GER-028	High Data Rate Return Link (Hybrid Radio Frequency (RF)/Optical Comm)			●	●
Power					
GER-011	High Strength/Stiffness Deployable Solar Arrays for Surface Exploration		●		●
GER-012	Autonomously Deployable High Power In-Space Arrays			●	
GER-013	Fission Power for Surface Missions				●
GER-015	Regenerative Fuel Cells		●		●
GER-017	Low Temperature and Long Life Batteries		●		
GER-067	Solid Oxide Fuel Cell				●
Infrastructure					
GER-045	Mars In-Situ Resource Utilization (ISRU)				●
GER-050	Dust Mitigation		●		●
GER-054	Inflatable: Structures & Materials for Inflatable Modules			●	●
GER-057	Low Temperature Mechanisms	●	●	●	
GER-063	Thermal Control		●		●

Table 5. EVA/Mobility/Robotics

Ref. Number	GER Critical Technology (all)	Lunar Vicinity	Lunar Surface	Mars Vicinity	Mars Surface
GER-019	Telerobotic control of robotic systems with time delay	●	●	●	●
GER-020	Robots Working Side-by-Side with Suited Crew		●		●
GER-031	Deep Space Suit (Block 1)	●		●	
GER-032	Lunar Surface Space Suit (Block 2)		●		
GER-033	Mars Surface Space Suit (Block 3)				●
GER-047	Rapid Access Extra Vehicular Activity (EVA)		●	●	●
GER-048	Surface Mobility Systems		●		●

Table 6. Autonomous Systems

Ref. Number	GER Critical Technology (all)	Lunar Vicinity	Lunar Surface	Mars Vicinity	Mars Surface
GER-020	Robots Working Side-by-Side with Suited Crew		●		●
GER-021	Autonomous Vehicle Systems Management	●	●	●	●
GER-022	Automated/Autonomous Rendezvous & Docking	●		●	
GER-023	Crew Autonomy beyond LEO	●	●	●	●
GER-027	In-Space Timing and Navigation for Autonomy			●	●
GER-049	Mission Control Automation beyond LEO			●	●