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ASSESSING SPACE EXPLORATION TECHNOLOGY REQUIREMENTS AS A FIRST STEP TOWARDS ENSURING TECHNOLOGY READINESS FOR INTERNATIONAL COOPERATION IN SPACE EXPLORATION

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Advancing critical and enhancing technologies is considered essential to enabling sustainable and affordable human space exploration. Critical technologies are those that enable a certain class of mission, such as technologies necessary for safe landing on the Martian surface, advanced propulsion, and closed loop life support. Others enhance the mission by leading to a greater satisfaction of mission objectives or increased probability of mission success. Advanced technologies are needed to reduce mass and cost. Many space agencies have studied exploration mission architectures and scenarios with the resulting lists of critical and enhancing technologies being very similar. With this in mind, and with the recognition that human space exploration will only be enabled by agencies working together to address these challenges, interested agencies participating in the International Space Exploration Coordination Group (ISECG) have agreed to perform a technology assessment as an important step in exploring cooperation opportunities for future exploration mission scenarios.

The *International Space Exploration Coordination Group* (ISECG) was established in response to *"The Global Exploration Strategy: The Framework for Coordination"* developed by fourteen space agencies[*] and released in May 2007. Since the fall of 2008, several International Space Exploration Coordination Group (ISECG) participating space agencies have been studying concepts for human exploration of the moon. They have identified technologies considered critical and enhancing of sustainable space exploration. Technologies such as in-situ resource utilization, advanced power generation/energy storage systems, reliable dust resistant mobility systems, and closed loop life support systems are important examples. Similarly, agencies such as NASA, ESA, and Roscosmos have studied Mars exploration missions and identified critical technologies. They recognize that human and robotic precursor missions to destinations such as LEO, Moon, and near Earth objects provide opportunities to demonstrate the technologies needed for a human Mars mission.

Within ISECG, agencies see the importance of assessing gaps and overlaps in their plans to advance technologies in order to leverage their investments and enable exciting missions as soon as practical. They see the importance of respecting the ability of any agency to invest in any technologies considered of interest or strategic. This paper will describe the importance of developing an appropriate international framework for technology assessment and development. This work will both inform and be informed by the development of an ISECG Global Exploration Roadmap and serve as a concrete step forward in advancing the Global Exploration Strategy.

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

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

INTRODUCTION

Space exploration has always heavily relied on highly advanced and complex technologies. In order to achieve the ambitious goals set out in the GES, many existing technologies need to be advanced and several novel technologies need to be made usable for space applications. The importance of a coordinated multilateral dialog on the technologies needed to enable complex human space exploration missions was introduced in the paper *From LEO, to the Moon and then Mars: Developing a Global Strategy for Exploration Risk Reduction*, IAC-09-B3.1.1.7 (Ref 1).

To increase the understanding of those future technology needs, many agencies have performed design reference missions to destinations of interest to the GES, e.g., ISECG Lunar Architecture Study and other lunar studies; Mars mission studies by NASA, ESA, Roscosmos, ASI; and Asteroid mission studies by NASA, JAXA. In each of these studies, commonalities of key capabilities and technology needs could be identified and they could be classified in ways considered useful for discussion, e.g., transportation, propulsion, power/energy, habitation, servicing, ISRU, EVA, communication and navigation. Among those, propulsion, power generation, precision landing, advanced life support, and autonomous rovers are examples of capabilities that require significant technology development.

A sustainable exploration vision relies on realistic resource planning. As shown in Figure 1, inadequate investment and knowledge about key technologies and design issues results in significant project cost impacts. Hence, risk and, in turn, cost reductions for missions can be achieved through specific and innovative mission classes, technology demonstration, precursor mission, and analogue deployments.

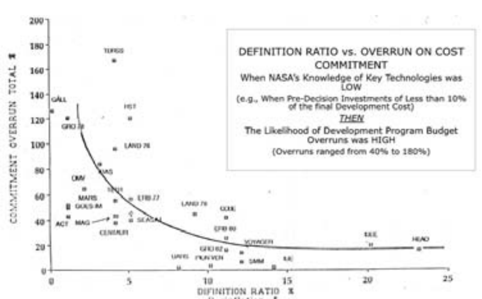

Figure 1: Tech. development vs. cost overrun†.

† NASA Internal Presentation; Werner Gruehl (1988)

Given the substantial amount of required technology developments and the acknowledged need for an affordable and sustainable human exploration beyond LEO, many agencies realize that internationally leveraging our technology investments is the only way to ensure success. To be successful, this requires a common framework to facilitate the exchange of information and create opportunities for coordination and cooperation on technology developments and demonstration. This paper describes an evolving concept for accomplishing these goals within the ISECG.

CAPABILITY AND TECHNOLOGY NEEDS

Through the various studies done for different GES destinations, capability and technology development needs have been identified. In the context of this work, "capabilities" refer to the main elements required to enable a space exploration mission such as launcher, in space transportation, orbiter, lander, habitat, rover, etc. Technologies that are required to develop these capabilities have also been identified. Technologies can have application in several different capabilities. For example, rovers may benefit from vision for navigation and manipulators for sample acquisitions. These vision systems and manipulators are technologies which are also required for orbiters providing on-orbit servicing.

A key element to start the discussion on capability and technology development is to agree on a classification method both for the capabilities and the technologies. The level of granularity, i.e. how deep we need to go especially for technology should be agreed in the beginning. Since this exercise of developing a framework or classification method is done as a basis for an international assessment and potential collaborations, there is no need to go very deep into the technology decomposition. In practice, two levels, one for the capability and one for the technology should be sufficient. A first step will be to survey the classification used by NASA, ESA, CSA, JAXA and other space agencies. It is recognized that these classifications normally use many levels and will be too complex for our application, but they will inform in international classification scheme and lexicon.

Once a framework, or classification system, has been established, participating agencies will focus on identification of capabilities and technologies considered critical and enhancing. By using capabilities as a main organizing principle, agencies believe that this framework will inform the assessment of any future human mission scenario. Basic capabilities, i.e. launchers, in space stages, etc are required in most human exploration scenarios.

Based on studies done by ISECG or by some of the participating agencies, a first list of destination specific challenges has been produced:

- ISS:
  - Reliable Closed-loop life support
  - Supportability & maintenance concepts
- Near-Earth Space: Lunar fly-by, lunar orbit, Libration Points
  - Heavy lift launch
  - Crew support for 14-30 days
  - Deep-space propulsion
  - Radiation protection
- Lunar Missions:
  - Landing systems
  - Surface systems
    - Mobility in dusty environment
    - Advanced EVA operations concepts
    - Human/robotic interaction
    - In-situ resource utilization
    - Autonomous/ tele-operated robotic systems
    - Advanced energy/ power systems
- Deep Space:
  - Crew support for long duration (habitat)
    - Radiation protection (habitat)
    - Closed-loop life support (habitat)
  - Deep space propulsion
    - Cryogenic fluid management
    - Nuclear propulsion
  - Automatic Rendezvous & Docking
  - Supportability & maintenance
- Mars Missions:
  - Mars entry & landing systems
  - Advanced propulsion
    - Cryogenic fluid management
    - Nuclear propulsion
  - Radiation countermeasures
  - Advanced avionics
  - Crew support/habitation
  - Surface systems (similar to Lunar missions)

The Importance of Maximizing Use of ISS

A key element discussed among the ISECG members is how to maximize use of the ISS as a demonstration platform for technologies developed for exploration. This is a key objective for the ISS participating agencies. While discussions are on-going on this subject, an initial list of potential demonstrations has been established, as shown in Table 1.

Technology, Research, or Demonstration	Specific Need
Zero-g countermeasures	Protocols and techniques
Closed-Loop Life Support	Water and gas closure. Low sparing. Low maintenance.
Radiation Protection	Protection, Biological countermeasures
Crew Support & Accommodations	Advanced systems integrated into core station or dedicated module
Cryogenic Fluid Management	Small scale zero-G conditioning and transfer
Robotics, Operations & Supportability	Advanced human scale robot with ground supervised or autonomous support
Atmospheric Revitalization	

Table 1: Opportunities for Using ISS to advance Exploration Technologies

CREATING AN ORGANIZING FRAMEWORK

An organizing framework for the advancement of critical and enhancing space exploration technologies is considered important if agencies are to realize the common goals embraced in the Global Exploration Strategy. However, given significant differences in the organization, function and priorities of agencies, an international technology assessment framework needs to be properly scoped, structured and kept at a high enough level to avoid getting unmanageable and ineffective. Several areas considered worthy of discussion are listed below.

Technology Readiness and Risk Assessment

Technology Readiness and Risk Assessment (TRRA) is recognized as a key to enable the definition of technology development programs, linking technology needs to mission scenarios, helping to streamline investment decisions while balancing the acceptable risks. On the national scale, a thorough TRRA facilitates better focused technology development programs and enables early risk retirement, therefore reducing mission costs and minimizing schedule delays. On the international scale, when agencies anticipate undertaking complex human missions together, a common TRRA can be invaluable to enabling a shared emphasis on technology demonstration and risk reduction.

TRRA closely linked to mission roadmaps allows leveraging technology developments across multiple missions as well as tailoring mission profiles along specific technology solutions. Good examples are so called "Flagship Technologies" at NASA and "Signature Technologies" at the CSA. In case of the latter, CSA Signature Technologies dovetail with CSA Mission Roadmaps that include missions to which the CSA could potential contribute or lead. While the CSA Signature Technologies influence which missions are part of CSA Mission Roadmaps, the roadmaps, in turn, direct the evolution of CSA Signature Technologies.

On the international level, it is anticipated that TRRA will be supporting the long-term effort of ISECG to develop a Global Exploration Roadmap (GER). While the complexity of coordination is much higher, the importance of a common understanding of risks and the opportunity to leverage resources is much higher as well. The key is sharing of appropriate information, leveraging opportunities for coordination and cooperation, and establishing national long-term roles on the international exploration scene, while stimulating competition for innovation.

The key mechanism enabling this international coordination of technology development is a common framework for TRRA. This framework should allow a common methodology, identification, and classification of technology requirements, typically derived from high-level user and system requirements.

While a mission dedicated TRRA calls for a detailed analysis at the sub-component level, the TRRA in support of national or international mission roadmaps will be typically limited to a high-level assessment, e.g., at the instrument level or higher. With the TRRA being an integral part of the mission roadmap development cycle, for given science and human space flight objectives, the number and scheduling of analogue deployments, DTOs, and precursor missions can be facilitated. It is needless to say that the greatest benefits are obtained when coordinating with the larger, international space exploration community, e.g., allowing testing of different or complementary technologies on joint missions.

The proposed ISECG mechanism to capture capabilities and missions, including analogue deployments, DTOs, and precursor missions, is the INTERnational Space Exploration Coordination Tool (INTERSECT), which is introduced later in this paper.

Assessing Technology Readiness

The basis of technology assessment is the Technology Readiness Levels (TRLs). TRLs are a set of management metrics that enable discipline-independent assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology — all in the context of a specific system, application and operational environment. NASA initiated the use of TRLs in the late 1970s. The U.S. Department of Defense, ESA and the CSA have also been using TRLs for some years, with varying degrees of emphasis, and often informally. Recently, seven space agencies developed a new document titled "Technology Readiness Levels Handbook for Space Applications". Since this document is being recognized by seven of the world's major space agencies, it will become de facto the international reference in TRLs.

J. Mankins[‡] also introduced the Technology Need Value (TNV) and the research and development (R&D) degree of difficulty (R&D3). The TNV is a more general figure of merit for use in expressing the degree to which a particular technological solution is needed to achieve the minimum requirements of a given system or mission. It correlates with the idea of a technology being "enabling". The use of TNVs enables clearer distinctions between technological alternatives that exist in many cases. The R&D3 is a discipline-independent metric that correlates to the probability that a given technology R&D effort will succeed or fail – i.e., R&D3 reflects how hard a given R&D effort is expected to be to accomplish. Although TRLs provide a very useful measure of the current level of maturity of a technology (i.e., the "readiness" of the technology to be used in a new system development or applications, the TRL scale does not provide any insight into how difficult progressing from one level to the next may actually be to accomplish. It may be very easy in one case to progress from TRL 3 (a preliminary experiment) to TRL 4 in one case and extremely difficult in another case. R&D3 gives the technology development manager a means of summarizing and comparing the "hardness" of various prospective R&D objectives.

With the help of those three figures of merit, technologists, systems developers and senior managers can define a common ground to discuss important technology investment decision, namely

- What is the current level of technology maturity (TRL);
- How hard is it advancing from the current TRL to the targeted one (R&D3); and
- How important is each specify technology for the success of the mission (TNV).

Moreover, a thorough technology readiness and risk assessment covering in particular the enabling technologies promotes a better risk evaluation and leads to timely technology development.

[‡] Technology readiness and risk assessments: A new approach. Acta Astronautica. 65(2009) 1208–1215

The collective effort of developing a common framework is may also serve to create partnership opportunities in the demonstration of technologies and, hence, facilitate making informed decisions on their roles and contributions in the implementation of the GES vision

INTERSECT

While the TRRA plays a critical role in the development process of the GER, the capability and mission database INTERSECT is another important element for the coordination of the international space exploration effort. The INTERnational Space Exploration Coordination Tool (INTERSECT) is one of the products under development within the activities carried out by the ISECG. It is a database gathering information on missions, payloads and capabilities available or under study or development within the ISECG participating agencies.

The purpose of this tool is to enhance the agencies' ability to identify areas for cooperation, and help inform their own national space exploration architectures to ensure the sum of the whole is greater than the individual parts. The INTERSECT aims to facilitate communication among agencies to identify more collaborative and integrated exploration efforts. Such tool has also been thought to identify gaps and overlaps with respect to the different architecture elements and as such to support decisions for new developments and collaborations.

The value of this system resides in the analysis of the data to:

- Standardise terminology for facilitating identification of common/shared interests;
- Support the assessment synergies/gaps/overlaps of space agency's interests for facilitating the identification of opportunities for cooperation;
- Support the harmonisation of space agency's architectures by ensuring interoperability for enhancing feasibility, cost-effectiveness, safety and redundancy;
- Facilitate the identification of needs for common architecture elements and capabilities; and,
- Support the comparison of capability development and mission roadmaps for harmonisation and identification of opportunities for cooperation.

The INTERSECT is a strategic planning tool to support the international coordination process as implemented by the ISECG. It serves as a repository of validated information on space agency's space exploration interests and plans. INTERSECT is a multi-layered product including catalogues of (a) exploration missions under discussion and (b) exploration capabilities under development or available.

For missions and capabilities, the database structure features classification by type and destination, a high-level summary, schedules, stakeholders (including lead agency and cooperation opportunities), and the status in the database, see also Figure 2.

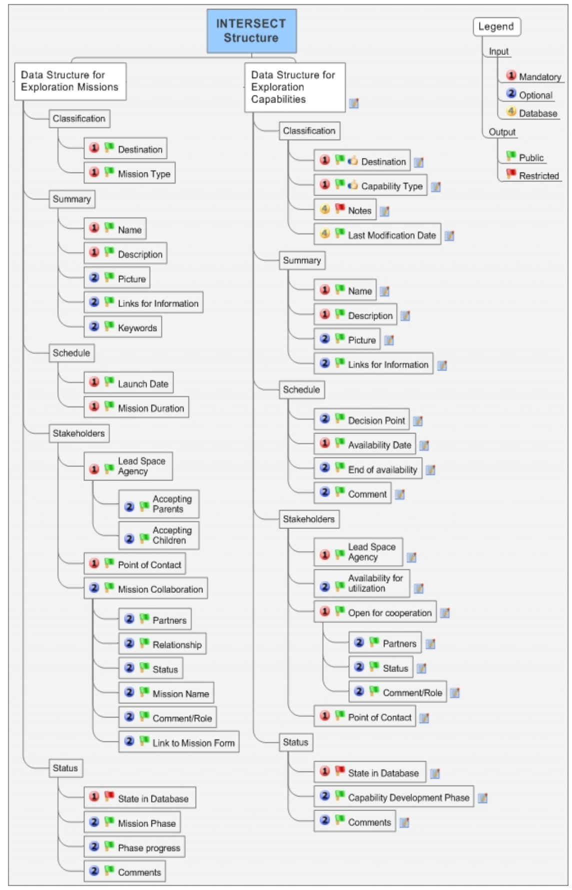

Figure 2: INTERSECT structure.

INTERSECT is developed and maintained through ISECG and is considered a critical support element to build a well informed global exploration roadmap and to be able to keep the latter up to date. ISECG will evaluate the role of INTERSECT in accomplishing its technology assessment goals.

THE IMPORTANCE OF RETAINING AGENCY AUTONOMY

Recognizing that individual space agencies have many reasons for investing in the technologies considered essential for space exploration, the technology assessment framework under the ISECG will be based upon the following tenets:

- Each agency retains autonomy to invest in any technology considered important, strategic or interesting. There is no intend to dictate or agree on who should develop a given technology. However, to get useful results, it will best if agencies are sharing their key technology areas. This will help others to focus their activities and make sure that there is no gap in the technology and capabilities;

- Some technology advancements benefit from competition. This is the case for most advanced technologies and a key driver for innovation;
- Some technology areas benefit from agencies making long term investment to enable dissimilar redundancy & multiple sources. This will help to ensure a robust and sustainable program. For example, having two different approaches for human launcher will reduce the risk;
- Each agency can develop key technologies at appropriate and affordable level. The technology assessment should not stop at main capabilities but should provide enough details so all agencies can find a role.

The GES document put a strong emphasis on the fact that no nation can do human exploration missions in isolation. The investment and the risks are too high. Since a mission is built on capabilities, and capabilities require technologies, some appropriate level of collaboration will be required between agencies. The ISECG technology assessment should find the balance and create a win-win situation so each agency can tailor a role adapted to its ambition and capacities.

RECOMMENDATIONS FOR FORWARD WORK

The ISECG will, in the near future, focus on facilitating interagency discussion to identify technologies considered critical to advance the GES, by

- Encouraging an international dialog on technologies that contribute to a more sustainable and affordable human exploration as key to our success. Participating agencies will be encouraged to share, at a level they feel appropriate, their capability and technology development plans. A potential approach is that agencies establish lists of key capabilities and technologies that they want to develop;
- Establishing a hierarchy of capabilities and technologies that is evolvable and aligned with international roadmap & architecture. This hierarchy or classification system should be established early in the process since it will be a key element in organizing the work;
- Performing an initial assessment focusing on missions identified to be part of the Global Exploration Roadmap and captured in INTERSECT. A key element at this point, is to do the assessment at the right level. Based on agency experience in this area, a detailed analysis will required too much resource to be justifiable;
- Identifying technology gaps. Such identification will require that agency share some of their development plan or niche area; and
- Fostering collaboration on technology demonstration in terrestrial analogues, on ISS or robotic missions. Such demonstrations are an excellent approach to explore collaboration for the development and deployment of capabilities and technologies. For example, NASA and CSA have been collaborating since 2005 on ISRU technologies and each agency was able to establish its role.

The proposed action plan was reviewed by the senior agency management (SAM) of the ISECG participating agencies during a meeting in June 2010. They asked ISECG to further advance the concepts introduced in this paper and recommend a way forward. The detailed approach and work plan should be finalized by mid-October.

The targeted timeline calls for an initial assessment to be completed by next SAM meeting planned for mid-2011 and regular revisits of the resulting product to ensure alignment with architectures, roadmaps and technology evolution.

ACRONYM LIST

- ISECG: International Space Exploration Coordination Group
- TRRA: Technology Readiness and Risk Assessment
- SAM: Senior Agency Management
- GER: Global Exploration Roadmap
- DTO: Detailed Test Objective
- GES: Global Exploration Strategy

REFERENCES

1 International Astronautics Congress (2009), Laurini, K; Hufenbach, B; Schade, B; Weber, P; Lorenzoni, A, “From LEO, to the Moon and then Mars: Developing a Global Strategy for Exploration Risk Reduction”, IAC-09-B3.1.1.7, Daejeon, S. Korea, September 2009