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Developing the global exploration roadmap: An example using the humans to the lunar surface theme

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A B S T R A C T

The development of the Global Exploration Roadmap (GER) by 12 space agencies participating in the International Space Exploration Coordination Group broadly outlines a pathway to send humans beyond low Earth orbit for the first time since Apollo. Three themes have emerged: Exploration of a Near-Earth Asteroid, Extended Duration Crew Missions, and Humans to the Lunar Surface. The lack of detail within each of these themes could mean that realizing the goals of the GER would be significantly delayed. The purpose of this paper is to demonstrate that many of the details needed to fully define and evaluate these themes in terms of scientific rationale, economic viability, and technical feasibility already exist and need to be mapped to the GER. Here, we use the Humans to the Lunar Surface theme as an example to illustrate how this process could work. By mapping documents from a variety of international stakeholders, this process can be used to cement buy-in from the current partners and attract new ones to this effort.

1. Introduction

The Global Exploration Roadmap [1,2] has been developed by the International Space Exploration Coordination Group (ISECG – comprised of 14 space agencies, 12 of which developed the GER; http://www.globalspaceexploration.org/wordpress/) to define a path to get humans beyond low Earth orbit and eventually to Mars. The path is visiting the lunar vicinity (including an asteroid brought there by a robotic mission), lunar surface, Mars vicinity, and finally the surface of Mars. While a conceptual outline for coordinated space exploration is articulated in this document, many details remain to be defined. In order that this document can be used to direct investment, architecture, and cooperative agreements, an expansion of the GER is required.

While the Apollo program served to demonstrate that one nation could send and return safely humans to the surface of another planet, the program was not sustainable and it was canceled in 1972. As humanity begins to reach for the stars once again, the lessons learned from Apollo need to be implemented. The importance of President George W. Bush's "Vision for Space Exploration" [3] has been underestimated because of the political rhetoric that surrounded its inception and execution [4]. It provided a focus for NASA and other space agencies to start the long-term objective moving humanity off planet to the Moon and beyond (*cf.* [5]), and a "Global Exploration Strategy" [6] was developed by 14 space agencies. However, with the change of administration in 2008, the US changed its approach on human exploration of the solar system.

In 2009, the Global Exploration Strategy set a top-level vision for human space exploration and was followed by the Global Exploration Roadmap (GER), which started the process of realizing the initial vision. The initial GER [1] espoused a flexible path to getting to Mars involving a Moon next or an asteroid next approach for human spaceflight. A study by Szajnfarber et al. [7] concluded that when international partners considered endogenously, the argument for a "flexible path" approach is weakened. This is because international contributions can make "Moon first" economically feasible, and characteristics of proposed flexible path approaches may preclude international involvement because of the disproportionate risk that those contributions inherently bear.

In 2013, a revised GER was published that dropped the flexible path approach in favour of a common pathway to Mars involving

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visiting the lunar vicinity, lunar surface, Mars vicinity and eventually Mars itself. Three near-term themes have emerged: Exploration of a Near-Earth Asteroid (in the lunar vicinity), Extended Duration Crew Missions, and Humans to the Lunar Surface [2]. As the feasibility of sending humans to a Near-Earth Asteroid in the relative near term has faded, a robotic Asteroid Redirect Mission (ARM) is now under consideration, with a small asteroid (or part thereof) being redirected to a stable lunar orbit for humans to explore. This would form part of the extended duration crew mission theme. Other options have been studied that could also form part of this theme, including placing the Crew Exploration Vehicle at Lagrange point 2 on the farside of the Moon and undertaking tele-robotic exploration of the lunar farside, including sample return and deployment of a radio telescope on the surface of the radio-quiet lunar farside [8–10].

The Humans to the Lunar Surface theme is probably the most advanced because of the work conducted following the announcement of the Vision for Space Exploration [3]. The latest version of the GER [2] further states that: “Many agencies consider human missions to the lunar surface as an essential step in preparation for human Mars missions”, and “Lunar missions are favored by agencies who view the Moon as the next step for human planetary exploration and NASA may contribute to such missions.” The recently published NRC report entitled “*Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration*” [11] provided a clear recommendation to extend a human presence beyond low Earth orbit (LEO). In the report a number of advantages to the United States being a more active player in lunar surface operations was emphasized. A return to extended surface operations on the Moon was recommended (i) to support the long-term strategy to land humans on Mars and (ii) to provide ample opportunities for international and commercial cooperation.

In this paper, we focus on developing the ‘Humans to the Lunar Surface’ theme of the GER [2] to illustrate that by mapping a number of recent reports/documents to it each theme can be developed. The other themes can be similarly developed and, as the title indicates, this study is an example. These documents are in no way meant to be encompassing everything that is relevant to this process (indeed, many others can and should be added). This exercise is intended to demonstrate that existing detailed documents can be mapped into the GER, despite the differences in focus and level of detail, and provides an avenue to promote broader international buy-in, especially from those ISECG agencies that are not part of the GER.

2. The global exploration roadmap (2013)

A brief overview of the GER is given in order that the mapping process outlined in this paper is put into context. The common goals are:

- Develop Exploration Technologies & Capabilities.
- Engage the Public in Exploration.
- Enhance Earth Safety.
- Extend Human Presence.
- Perform Science to Enable Human Exploration.
- Perform Space, Earth, and Applied Science.
- Search for Life.
- Stimulate Economic Expansion.

These rather broad goals lead to the six principles driving the mission scenarios and themes of the current GER: affordability, exploration value, international partnerships, capability evolution, human/robotic partnerships, and robustness. While the principle of robustness is articulated as “provide resilience to programmatic and technical challenges” it also implies sustainability. As Mars is currently termed the “horizon destination”, the GER has the opportunity to provide not only a pathway to Mars, but also to include and highlight opportunities to make the pathway sustainable. This principle, we believe, has its origins in the goal to stimulate economic expansion.

When detailing the humans to the lunar surface scenario, the GER gives a number of activities that will be woven into such missions:

- Technology test bed (surface power systems, long distance mobility concepts, human-robotic partnerships, precision landing).
- Characterizing human health and performance outside Earth's magnetosphere and in a reduced gravity environment.
- Conducting high priority science benefiting from human presence, including human-assisted lunar sample return.
- Advance knowledge base related to use of lunar resources.
- Explore landing sites of interest for extended durations.

For the purposes of this paper, these activities will form the basis of our mapping activity as an example to demonstrate that much of the work to develop the GER has already been conducted. There have been many studies since Apollo on returning to the Moon, and these are still valid. By recognizing the existence and utility of these documents, the ISECG can focus on developing mission concepts.

3. The mapping process

The documents used here represent a selection of internationally authored papers as well as documents from the Lunar Exploration Analysis Group (LEAG) that includes the extensive Lunar Exploration Roadmap. The documents are as follows:

- The Committee on Space Research (**COSPAR**) Panel on Exploration report on developing a global space exploration program [12],
- The Strategic Knowledge Gaps report from the LEAG (**LEAG–SKGs**) published in 2012 [13],
- The Lunar Exploration Roadmap developed by LEAG (**LEAG–LER**), which is updated periodically [14],
- The National Research Council report Scientific Context for the Exploration of the Moon (**SCEM**) published in 2007 [15],
- The Scientific Rationale for resuming lunar surface exploration (**SR**) [16], and
- The astrobiological benefits of human space exploration (**ASTROBIO**) [16,17].

The abbreviations used to designate each publication are in parentheses and bold type. For this activity, we tried to map each of the publications to the activities envisaged for the Humans to the Lunar Surface theme. Much more detail is given in the individual publications and we only summarize the main points here.

3.1. Technology test bed

The Moon represents a key asset for testing planetary exploration technologies because of its proximity to Earth. The GER is quite expansive about such issues listing one high-level common goal of “Develop Exploration Technologies & Capabilities” and one specifically under the humans to the lunar surface category [“Technology test bed (surface power systems, long distance mobility concepts, human-robotic partnerships, precision landing)”].

3.1.1. COSPAR

Synergies of robotic/human exploration and the Robotic Village concept of ILEWG and ILRP are described as examples of how the Moon can be used as a technology test bed for Solar System exploration. Robotic precursor missions will be required to pave the way to sending humans back to the lunar surface for periods longer than was achieved during Apollo. In addition, human-robotic partnerships could increase efficiency and productivity of any human mission to the lunar surface. The creation of a Robotic Village to prepare for an extended human presence on the Moon was endorsed by the International Lunar Exploration Working Group (ILEWG) in 2008 and 2010 [18,19].

3.1.2. LEAG-SKGs

There are many SKGs highlighted that relate to the topic of technology test beds that that can be found under SKG Theme III [13] and these include:

- Dust Remediation.
- Mitigating Mechanical Degradation of Regolith Adhesion.
- Descent/ascent engine blast ejecta.
- Energy Storage.
- Power Generation.
- Lander Propellant Scavenging.
- Radiation Shielding.
- Micrometeorite Shielding.

3.1.3. LEAG-LER

This roadmap is forward looking in that it proposes to use the Moon to go elsewhere in the Solar System [14]. There are three themes around which the roadmap is built: Science, Feed Forward (to Mars and other airless bodies), and Sustainability. Under the Feed Forward theme, there are several goals and objectives that relate directly to technology:

- *Goal FF-A*: Identify and test technologies on the Moon to enable robotic and human Solar System science and exploration. Under this goal there are six Objectives that directly use the Moon as a technology test bed (Objectives FF-A-1, 3, 5–8) that involve 23 individual Investigations.
- *Goal FF-B*: Use the Moon as a test bed for missions operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond. Under this goal there are three Objectives (FF–B-1, 2, 3) that involve 13 Investigations that use the Moon as a technology test bed to enable human Solar System exploration.
- *Goal FF-C*: Preparing for future missions to other airless bodies. Under this goal there are five Objectives (FF–C-1-3, 7, 9) involving 23 Investigations that can be directly related to using the Moon as a technology test bed.

The reader is directed to the latest version of the roadmap on the LEAG website (www.lpi.usra.edu/leag) for more information about the Goals, Objectives, and Investigations noted above.

3.1.4. SCEM

While this report focused on lunar science and was written in response to President Bush's Vision for Space Exploration, it did report a finding regarding the state of technology to achieve a human lunar return in preparation to go to Mars and beyond. Finding 3R of the SCEM Report [15] states "*NASA, with the intimate involvement of the science community, should immediately initiate a program to develop and upgrade technology and instrumentation that will enable the full potential of the VSE. Such a program must identify the full set of requirements as related to achieving priority science objectives and prioritize these requirements in the context of programmatic constraints. In addition, NASA should capitalize on its technology development investments by providing a clear path into flight development*."

3.1.5. SR

As with the SCEM Report [15], Crawford et al. [16] focus on the scientific rationale for resuming human lunar exploration. Implicit in this paper is using the Moon to test robotic sample return technologies, as well as human-robotic interactions (e.g., [8]).

3.1.6. ASTROBIO

Crawford [17] and Crawford et al. [16] concluded that the Moon could be used as a test bed for the development of bioregenerative life-support systems and for long-term use on the Moon and future long-duration deep space exploration missions. These conclusions were subsequently articulated in more detail by Goswami et al. [20].

3.2. Human health

The major research platform for studying the effects that space exploration can have on human health is currently the International Space Station (ISS). However, the ISS is not ideal for examining the effects of space radiation (as it is within the Earth's magnetic field) or the effects of reduced gravity on the human physiology. For example, we have a knowledge base on how the human body reacts to Earth's gravity and at microgravity (from the ISS and its precursors), but is there a linear relationship between the two extremes? Long duration human missions to the lunar surface should be able to inform us on this issue.

3.2.1. COSPAR

Ehrenfreund et al. [12] highlighted the ISS as the place where the most research is currently being conducted regarding the impact the space environment has on human health. These authors noted the European research on the ISS includes radiation biology and physiology, as well as health care and human performance under extreme conditions. Ehrenfreund et al. [12] also highlighted the US NRC Report [21], where both physical and psychological effects of space exploration are discussed. Finally, this document noted that space radiation is a major barrier to human exploration of the Solar System and concluded that environmental characterization, as well as materials testing should be conducted by robotic precursor missions, and that a focus on space weather prediction should be made.

3.2.2. LEAG SKGs

Theme II of this report [13] is focused on understanding the lunar environment and its effects on human health. SKGs noted under this theme were:

- Solar event prediction.
- Defining the radiation environment at the lunar surface.
- Understanding the radiation shielding effect of lunar materials.
- The biological effects of lunar dust.
- How to maintain peak human health and performance in dusty, high-radiation, partial gravity environments

3.2.3. LEAG-LER

Human health is a theme that pervades through the LER [14]. In the Science theme, Goal Sci-D is to use the unique lunar environment as a research tool. Objectives Sci-D-12 through 22 focus on the life sciences, with three of these being the most pertinent:

- Objective Sci-D-14: Study the fundamental biological and physiological effects of the integrated lunar environment on human health and the fundamental biological processes and subsystems upon which health depends.
- Objective Sci-D-15: Study the key physiological effects of the combined lunar environment on living systems and the effect of pharmacological and other countermeasures.
- Objective Sci-D-16: Evaluate consequences of long-duration exposure to lunar gravity on the human musculo-skeletal system.

The Feed Forward theme contains two Objectives (7 Investigations) related to human health:

- Objective FF-A-2 and FF-C-8: Develop Crew Health Systems That Enable Safe, Long Duration, Surface Stays.

In the Sustainability theme, human health issues are less obvious, being described at the initiative level under Goal Sust-B (enable and support the collaborative expansion of science and exploration) and within Objective Sust-B-8 (deployment of habitat and laboratory facilities for human science and exploration operations):

- Initiative-Sust-B-8A: Characterize aspects of the lunar environment that affect human health and safety including lunar regolith dust, radiation, temperatures, etc.
- Initiative-Sust-B-8B: Develop reliable space weather prediction, monitoring, and mitigation technologies.
- Initiative-Sust-B-8C: Develop long-term human health care and monitoring for lunar gravity conditions including any needed countermeasures, tele-medicine, monitoring devices and instruments, drugs, etc.

3.2.4. SCEM

Understanding the pristine lunar environment is important for designing mitigation technologies in order to provide safe living and working conditions. Therefore the SCEM Report [15] maps to this through "*Priority 8 - Processes involved with the atmosphere & dust environment of the Moon are accessible for scientific study while the environment is in a pristine state*."

3.2.5. SR

Crawford et al. [16] emphasized the importance of using the Moon to understand the effects of the space environment on human health: 1) Monitoring human adaptation to prolonged exposure to partial gravity may offer significant insights into vestibular disorders and a range of processes beyond associated in aging, disuse-pathology and lifestyle conditions such as the metabolic syndrome and cardiovascular disease; and 2) There would be much to learn about life support (e.g., bio-regenerative food, breathable air, and water closed-loops), and medical support provision, from human operations in a lunar base beyond research into partial gravity effects.

3.2.6. ASTROBIO

Use of the Moon to understand the long-term effects of the space environment (e.g., the radiation, microgravity, psychological aspects) is required because our knowledge is not sufficient [17]. Several areas of investigation are highlighted: Study of the adaptation of terrestrial life to the lunar environment; Use of the lunar environment: for *panspermia* experiments and as a test bed for planetary protection protocols; as a test bed for the development of bioregenerative life-support systems, for long-term use on the Moon and future long-duration deep space exploration missions (see also [20]).

3.3. Conducting high priority science benefiting from human presence, including human-assisted lunar sample return

This is the easiest of the GER goals to map existing documents to for the humans on the lunar surface theme. Learning from the Apollo experience, where science was an afterthought, the international lunar community has been proactive in documenting the importance of science in any program that returns humans to the lunar surface. Ehrenfreund et al. [12] noted that sample return missions (both human assisted and robotic) have the highest priority for the science community. They also noted that planetary science stands to be a major beneficiary of human space exploration.

Addressing any of the LEAG-SKGs under theme I (Understand the lunar resource potential) will inform both lunar and planetary science. This is exemplified by any mission that addresses SKG I-D: Composition/quantity/distribution/form of water/H species and other volatiles associated with lunar cold traps. In addition, the LEAG-LER Science goal documents critical unanswered science questions including lunar (Goal Sci-A: *Understand the formation, evolution, and current state of the Moon*), Solar System (Goal Sci-B: *Use the Moon as a "witness plate" for solar system evolution*; Goal Sci-C: *Use the Moon as a platform for Astrophysical, Heliophysical, and Earth-Observing studies*), and applied science (Goal Sci-D: *Use the unique lunar environment as research tool*).

The SCEM [15] report and Crawford et al. [16] both documented high priority science associated with returning humans to the Moon. In addition to the clear benefits to lunar and planetary science resulting from sample acquisition, and the deployment of geophysical instruments, these scientific benefits include the use of the lunar surface as a platform for astronomical observations. In particular, the lunar farside is arguably the best location in the inner Solar System from which to conduct low-frequency radio observations of the early Universe (*cf.* [8,10]), and the lunar surface may also lend itself to other areas of astronomical observation (*cf.* summary provided by Ref. [9]).

Crawford [17] (ASTROBIO) focused on documenting the scientific benefits for astrobiology of humans returning to the Moon. These include the study of the lunar geological record to elucidate conditions on the early Earth under which life took root on our planet, the study of possible pre-biological chemical evolution in polar ices, and studies of the adaptation of life to the low gravity, high-radiation environment of the lunar surface (*cf.* [22]).

3.4. Advance knowledge base related to use of lunar resources

It has been known since the Apollo that the Moon is home to resources that could be used to facilitate human space exploration. The initial work on this subject is probably best captured in the Lunar Bases and Space Activities for the 21st Century conferences [23,24] and the Space Resources report [25]. Since that time, lunar volatiles have become an intensive topic of lunar research (e.g., [26–36]) and could form the basis of an important natural lunar resource. LEAG has also proposed a plan to implement their roadmap [14] by identifying, prospecting, and developing lunar resources, which would provide commercial on-ramps for private companies to become involved in lunar exploration, thus bringing the Moon into our economic sphere of influence (see Ref. [37] for details).

3.4.1. COSPAR

Ehrenfreund et al. [12] listed technologies needed to prepare for human exploration of the Moon. These included in situ resource utilization (ISRU) and energy production and storage. They concluded that "*Comprehensive studies and multidisciplinary analyses* *are needed to … . develop evolutionary concepts for making use of local resources to enable sustainable human presence and fruitful operations on the surface of Moon and Mars*." They also supported studies and precursor activities toward developing "international human bases", as well as **s**ample return missions to the Moon, near-Earth asteroids and Mars. Implicit in these is the development of ISRU capabilities that would facilitate human space exploration.

3.4.2. LEAG-SKGs

Theme I of the SKG document is devoted to understanding the lunar resource potential. The SKGs noted under this theme include solar illumination mapping, regolith studies (quality/quantity/distribution/form of H species and other volatiles in mare and highlands regolith), study of volatiles associated with lunar cold traps and pyroclastic deposits, and the efficiency of lunar ISRU production. This document also defines a number of SKGs specific to lunar cold trap volatile deposits:

- Extent, magnitude and age of cold traps
- Correlation of cold traps and permanent darkness (PSR)
- Geotechnical characteristics of cold traps
- Physiography and accessibility of cold traps (robotic and human)
- Charging and plasma environment within and near PSR
- Earth visibility timing and extent
- Concentration of water and other volatiles species with depth at 1–2 m scales
- Variability of water concentration on scales of 10's of meters
- Mineralogical, elemental, molecular, isotopic make up of volatiles
- Physical nature of volatile species
- Spatial and temporal distribution of OH and H_2O at high-latitudes
- Detect and measure exospheric water in association with surface-correlated deposits
- Monitor and model movement towards and retention in PSRs

Also, Finding 3 of the LEAG SKG report states "*resource exploration and utilization (ISRU) is a "game changer" in how humans explore the Solar System by creating an infrastructure that enables a sustainable human presence*".

3.4.3. LEAG-LER

The LER includes a number of objectives throughout all three themes that are related to ISRU. Under the Science theme:

- **Objective Sci-A-3**: Characterize the environment and processes in lunar polar regions and in the lunar exosphere (4 Investigations);
- **Objective Sci-D-8**: Investigate precipitation behavior in supercritical water in partial gravity environment (2 Investigations);
- **Objective Sci-D-9**: Investigate the production of oxygen from lunar regolith in lunar gravity (2 Investigations);

Development of ISRU capabilities is also highlighted in the Feed Forward theme:

- **Objective FF-A-4**: Develop the capability to acquire and use local resources to sustain long-term exploration and habitation of planetary surfaces (6 Investigations);
- **Objective FF-C-10**: Develop the capability to acquire and use local resources to sustain long-term exploration crews (Corollary of Feed-Forward Objective FF-A-4) (3 Investigations);

The identification, extraction, storage and use of in situ resources form the foundation of the Sustainability theme. ISRU provides on ramps for commercial participation because it results in a product that can be sold initially to government entities (space agencies), but as lunar development continues, space agencies will leave to go to Mars and beyond. It is envisaged that private companies will lease the infrastructure from governments and these will become the next tier of customers for ISRU products. Therefore, Goal Sust-A is to maximize commercial activity with ISRU at the core of activities under this goal. Goal Sust-B is intended to enable and support the collaborative expansion of science and exploration. Under this goal, ISRU is represented by Objective Sust-B-9 - *Establishment of in-situ production of life-support, power system reagents, propellants and related resources*, and there are ten Initiatives under this objective all related to development of products from resources available on the Moon. Goal Sust-C is intended to enhance security, peace, and safety. ISRU is represented by Objective Sust-C-2 – Beamed power and other lunar-based energy sources for terrestrial consumption, which is also considered a commercial on ramp. Identification of polar areas receiving maximum sunlight will be part of fulfilling this objective (*cf.* [38,39]).

As noted above, LEAG developed an approach to implement the LER through a phased robotic precursor campaign in 2011 [37]. Phase I would undertake resource prospecting using the global datasets from previous and current orbital missions to identify the most promising deposits. Mobile surface assets (rovers) would be sent to the most promising deposits to map and quantify the deposit. Such rovers would need to be able to sample the subsurface. The US Resource Prospector Mission from the Human Exploration and Operations Mission Directorate of NASA is a first step along this path (e.g., [40]) and is currently due to launch on 2019. Phase II requires lunar robotic resource mining operations to be set up at the 2-3 most promising deposits identified in Phase I. These would demonstrate the "extractability" and yield of the potential resource. Phase III would be full lunar resource production at the best site identified in Phase II.

3.4.4. SCEM

ISRU is listed in the SCEM [15] report under secondary goals that would be oriented towards exploration (rather than science). However, it is evident that science and exploration are intimately related and that one informs the other. Therefore, addressing Priority 4 (The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history) would also yield information pertinent to ISRU.

3.4.5. SR

The Moon is the type locality to study volatile loss, transport, and retention on airless bodies Better characterization of the composition, volatile content, and mechanical properties of lunar regolith will also be important for planning and developing ISRU. This is because many volatile species implanted by solar wind are only loosely bound and the returned samples may have lost a good portion of these. Crawford et al. [16] also noted the importance of the polar regions and the permanently shadowed craters in particular for preservation of volatile deposits. Such deposits would represent targets for in situ resource applications.

3.4.6. ASTROBIO

Crawford [17] and Crawford et al. [16] noted that it is possible that some information concerning the importance of comets in "seeding" the terrestrial planets with volatiles and prebiotic organic materials can be found in the polar ice/volatile deposits. Lunar polar ice/volatile deposits will have been continuously subject to irradiation by cosmic rays and, as such, may have played host to organic synthesis reactions of the kind thought to occur in the outer Solar System and on interstellar dust grains. These papers demonstrate the potential that development of polar deposits for resources to support human exploration will also result in significant science return.

3.5. Explore landing sites of interest for extended durations

Identification of lunar landing sites for science and exploration purposes has been ongoing for several decades (e.g., [41–45]). For example, De Rosa et al. [46] proposed landing sites in the south pole region of the Moon for ESA's solar powered Lunar Lander project, which used knowledge of illumination conditions to highlight sites that experienced relatively short periods of darkness (tens of hours). The GER can be linked to these documents, but those chosen for this mapping exercise also contain pertinent information about site selection.

3.5.1. COSPAR

In terms of lunar site selection that would enable human exploration for extended durations, Ehrenfreund et al. [12] point to areas of quasi-permanent illumination in the polar regions (e.g., [37,38]).

3.5.2. LEAG-SKGs

Solar illumination mapping is highlighted as enabling polar exploration mission site selection. Filling SKGs regarding lunar surface trafficability will enable the characterization of a site for building-up assets for extended duration activities, it enhances exploration of unexplored areas, and is required for large-scale ISRU production (see above). Identification of potential resources using orbital datasets followed by the LEAG three-phase exploration strategy (see above) is also highlighted and is very relevant the GER.

3.5.3. LEAG-LER

Site selection is encapsulated in the Sustainability theme in Objective Sust-B-2: Establishment and implementation of comprehensive site-selection criteria and processes. The description of this objective contains important considerations given the inevitable multi-national approach that will be taken as humans step beyond LEO for the first time since 1972:

> The selection of sites for the emplacement of assets for scientific investigations or exploration activities is a rare occasion resulting in the commitment of substantial and possibly irreplaceable resources. The various parties interested in the properties of the selected site may have differing objectives for its collaborative use suggesting both a need for balanced negotiations and the best obtainable data from the candidate locations. In addition to considering the viewpoints of all partners, governmental, commercial, academic, and the international counterparts of each of these, practical operational considerations are crucial including transportation, communication and power availability, local resource availability and geological features amenable to well-protected human habitats.

3.5.4. SCEM

The SCEM Report [15] focuses on addressing major lunar science questions. However, the report does address landing sites, but to address science goals. For example, Finding 2R states:

> Critical to achieving high science return in Apollo was the selection of the lunar landing sites and the involvement of the science community in that process. Similarly, the scientific community's involvement in detailed mission planning and implementation resulted in efficient and productive surface traverses and instrument deployments.

This finding produced Recommendation 2R:

> The development of a comprehensive process for lunar landing site selection that addresses the science goals.… … …in this report should be started by a science definition team. The choice of specific sites should be permitted to evolve as the understanding of lunar science progresses through the refinement of science goals and the analysis of existing and newly acquired data.

The SCEM [15] discusses the dichotomy between sortie missions to different locations (ideal for addressing lunar science questions) and building up assets at one outpost site (ideal for exploration). The report concludes that the precise location of an outpost site will determine the scientific return and urges NASA to consider scientific criteria in the site selection process.

3.5.5. SR

Similar to the SCEM report, Crawford et al. [16] also articulated (but more broadly) the scientific rationale for returning to the lunar surface. As such, many different landing sites are suggested to address the science questions. This leads to the conclusion that a build up of assets at any one site for extended duration missions to the lunar surface should consider including surface mobility (human-rated exploration rovers, hoppers, etc.). Alternatively, strategic robotic missions to the lunar surface to achieve science goals could be envisaged in conjunction with humans on the lunar surface.

3.5.6. ASTROBIO

Crawford [17] concluded that for astrobiological goals, development of launch vehicles (and associated infrastructure) to return humans to multiple sites on the lunar surface for extended periods should occur. This would allow humans to conduct geological and biological fieldwork to address the various astrobiology science questions noted in this paper.

4. Synthesis

The goal of this exercise is to demonstrate that, using the Humans to the Lunar Surface theme of the GER [2] as an example, existing international documents map directly in to this roadmap and thereby strengthen it. The number of publications involved in this mapping process is admittedly small, but the concept has been demonstrated; additional international material will be incorporated in the future. Although the GER [2] is written at a high level, detail can be added through linking such documents to it. We envisage the next stage of GER development should include detailed mapping efforts within the different themes that comprise the pathway to Mars by setting up a number of working groups comprised of experts within the respective fields, ranging from science and technology to policy. It is vitally important that communication between the different stakeholders (including international partners as well as the broader science and engineering communities) be maintained, allowing for progress to made to achieving the near-term goal of sending humans beyond low Earth orbit, while maintaining focus on the horizon goal. By making such progress, technological innovations, growth in high-technology jobs, and economic growth will follow as has been demonstrated by the Apollo program (e.g., [47,48]) and the U.S. Space Program since then [49].

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