The Whole is More than the Sum of its Parts: Updates from the TURTLE Group Towards The Global Development of a Lunar Exploration Technology Adaptive Roadmap

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Abstract

Space resource activities (SRA) are the key to successful and sustainable space exploration. However, to unleash their transformative potential they need to be integrated into a broader ecosystem designed to maximize the benefits of in-situ resources utilization. At present, space resource missions are planned as if they were to happen in isolation. Besides vague plans for the commercial utilization of lunar ice as propellant, space resource operators are not really factoring the activities conducted by other operators into their own plans. This lack of holistic thinking becomes a major weakness with respect to the development of appropriate infrastructure enabling the safe and sustainable conduct of space resource activities. At the very least, each SRA will need power systems, storage facilities and transportation infrastructure. On a small body such as the Moon, this kind of foundational infrastructure should be jointly developed by all interested actors in order to reduce costs, prevent harmful interference and minimize the impact on the environment.

To begin a global conversation for the holistic design of foundational, interoperable and multi-purpose lunar infrastructure, in September 2020 a group of young researchers from the Space Generation Advisory Council (SGAC) came together to form the Technical Unit Research for a Thriving Lunar Ecosystem (TURTLE). After one year of foundational research on key areas for lunar development - landing sites, power systems, logistics, biospheres and dust mitigation - the TURTLE Group has established a baseline for the global development of a Lunar Exploration Technology Adaptive Roadmap (LETAR). The LETAR is meant as a shared reference framework across all lunar actors driving and supporting lunar sustainable development through technological inclusiveness, efficiency, interoperability and adaptability.

The proposed work would present the benefits offered by LETAR for the safe and sustainable utilization of space resources on the Moon, and discuss the foundational baseline established by the TURTLE Group as a starting point for its shared development with all interested actors.

Keywords: space resources, lunar governance, Moon exploration, international cooperation, space policy

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Introduction

The Moon is at the center of a renowned global interest for space exploration. As the most logical next step in the expansion of human presence beyond Low Earth Orbit and a steppingstone to Mars, Earth's natural satellite is set to become the stage of a multitude of activities that will reshape humanity's perception of its role and position in the Universe.

As part of these plans to return to the Moon, technology roadmaps are constantly developed by space agencies, universities and private entities with the purpose of mapping the current landscape of available technologies and planning their development in order to accomplish future missions. These roadmaps are commonly realized in the form of taxonomies, whereby technology is broken down into a set of principal domains (e.g. propulsion, navigation, energy systems) that further branch into more specific subdomains (e.g. electric propulsion, chemical propulsion, etc.) and ultimately into individual components and parts with measurable performance metrics to be improved as the results of the proposed advancement efforts (e.g. higher specific impulse for solid propellants). The principal domains are chosen based on a set of high priority needs and goals, which inform the overall technology development trajectories.

However, current roadmaps have several limitations. First, they often take the perspective of a single organization [1][2], which leaves virtually no room for sustained contribution from other entities. This also implies that the set of priorities and future missions that drive the proposed technology development efforts are more vulnerable to modifications imposed by changes in leadership, thus compromising long-term visions for technology development. This issue has been addressed in some cases by organizations such as the Lunar Exploration Analysis Group [3] and, most traditionally, by the International Space Exploration Coordination Group [4]. However, these roadmaps lacked the perspective of international private and commercial players - especially New Space companies and civil society organizations. This issue has been partially addressed by de Weck and co-workers, who published a Commercial Space Technology Roadmap in 2018 [5]. In addition to the technological breakdown, the work mapped the technologies to the companies working on their development, and provided valuable intelligence on patenting activity and government funding in each sector.

But ultimately, the most critical limitation of existing roadmaps is of a conceptual nature. Until now, the purpose of all existing roadmaps has been to capture, in one document, a sequence of planned missions on a given celestial body under a given timeframe. Existing roadmaps are essentially *descriptive* documents: they report and elaborate on plans that have already been decided. To be sure, they are certainly useful to understand the likely evolution of the status quo. However, if we are to establish a permanent presence on the Moon in a safe and sustainable manner, we need more than descriptive tools. We need a shared reference document that indicates what *should* be done in order to achieve this ambitious goal. We need it to bring order and coherence in the currently fragmented approach to lunar development. Based on these reasons, we argue for the development of new kinds of roadmaps meant to clarify the conditions that have to be fulfilled for the successful realization of our desired future on the Moon.

1. Towards holistic technology development: introducing the Technical Unit Research for a Thriving Lunar Ecosystem (TURTLE) and its proposal for a Lunar Exploration Technology Adaptive Roadmap (LETAR)

With the above premises in mind, in September 2020 a group of young researchers from the Space Generation Advisory Council (SGAC) came together to form the Technical Unit Research for a Thriving Lunar Ecosystem (TURTLE), with the goal to kickstart a global conversation on the holistic design of foundational, interoperable and multi-purpose lunar infrastructure.

The defining feature of the TURTLE Group is the conduct of strategically oriented research combining the findings developed as a result of in-depth assessments of selected foundational areas for lunar development under a systemic approach.

The main goal and feature of the TURTLE project are reflected in the structure of the Group, which includes seven teams of international young experts researching on as many foundational areas, as shown in the Figure below. During its first years of operations, the TURTLE Group conducted foundational research on key areas for lunar development [1-5], those being landing sites, power systems, logistics, biospheres and dust mitigation. Building upon these initial studies, at the 72nd International Astronautical Congress (IAC) the TURTLE Group presented the first baseline for the global development of a Lunar Exploration Technology Adaptive Roadmap (LETAR). LETAR is meant as a shared reference framework serving all lunar actors and driving the sustainable development of the Moon through technological inclusiveness, efficiency, interoperability and adaptability. Leveraging the feedback received at the 72nd IAC, the TURTLE Group has been recently expanded with the addition of two teams dedicated to *in-situ* resources utilization and environmental sustainability. Throughout a series of regular interactions and exchanges among these teams, new findings are being gathered, merged and fed into the LETAR baseline, which will be presented in the next section.

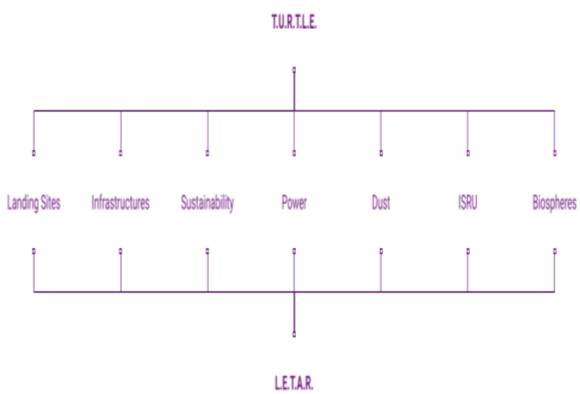

Figure 1. T.U.R.T.L.E. research areas feeding into L.E.T.A.R.

A brief summary of the main preliminary findings developed by the TURTLE teams - and thus of the foundational elements composing the LETAR baseline - is provided below.

Landing Sites

The research conducted within the Landing Sites team started from a grassroots assessment of the forthcoming lunar missions, in order to map planned landing sites and locations of interest [6]. This initial dataset has been examined to identify those regions whose morphological, *selenological,* and environmental features are expected to attract the largest number of actors or the most intense or recurring activity. *Inter alia*, factors such as proximity to water, volatiles or other precious minerals reservoirs, illumination patterns, telecommunications, radiation and meteoroid impact exposure, land slope or absence of major roadblocks for transport, mobility and landing have factored into the study. Figure 1 below shows a map of favorable landing sites in proximity of Permanently Shadowed Regions (PSR) based on terrain slope, obtained using GIS data.

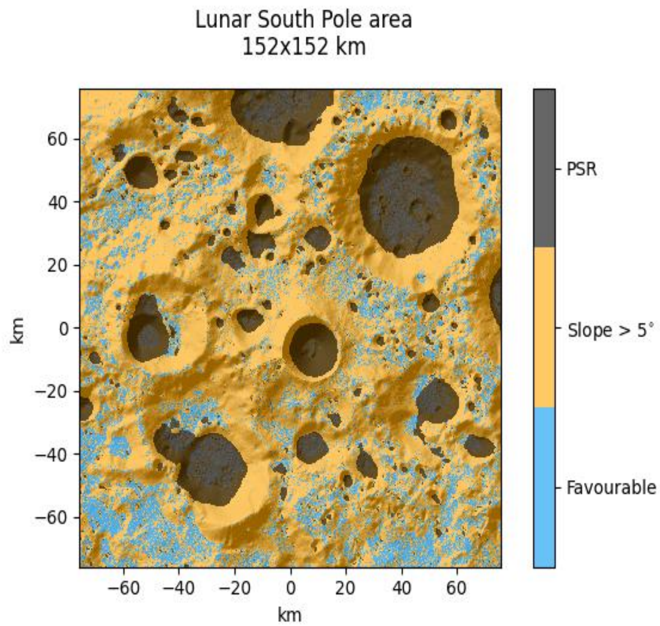

Figure 2: Map of favorable landing sites in the proximity of PSRs based on terrain slope

The attractive conditions offered by the identified landing sites naturally turns them into the most suitable candidates for the establishment of lunar ports. In fact, these features are not only at the core of many prospective lunar missions, but they also provide foundational resources to support various services that could be made available to all lunar operators in an effort to increase access to the lunar surface. These services may include, to name the most critical ones, shared landing pads, refueling stations, vehicle maintenance and inspection, water provision for astronauts, transport of goods and parts and connections to bases and mission sites, landing and take-off assistance and traffic control. The establishment of these services and the required technologies have been examined and attributed with a priority level according to three time horizons: in 2024, by 2054, and after 2054.

Power

The Power team has conducted an extensive trade-off study of the state of the art of the main power technologies, broken down into the three main segments of the energy value chain: generation, distribution and storage [7]. The analysis has been conducted targeting those technologies that can play a critical role in the provision of reliable energy at high power levels - in the order of 10 kW - to a multitude of international actors sharing the same infrastructure. The most promising technologies have been selected on the basis of a series of technical performance metrics - such as power density, energy density, system mass to distribute energy across unit distances - as well as qualitative metrics that are relevant for the collective scenario being considered, such as scalability and interoperability. Each of these metrics for the identification of the best combination of power generation, distribution and storage has been attributed a different weight according to the lunar region it would be deployed in, such as permanently shadowed regions or lunar pits. Using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a suitability score was determined for each technology and every region of interest. Finally, a sensitivity analysis determined the metrics where a unit improvement would have the greatest impact on the overall suitability of each technology for the purposes described above, in order to inform and optimize the efforts to develop shared energy hubs. Figure 2 below shows the result of a sensitivity analysis on energy storage technologies for PSRs. The vertical bars indicate the gain in suitability score per unit improvement in any given performance metric reported on the right horizontal axis. In this case, for instance, an improvement in power density shall be prioritized in order to most effectively advance regolith usage as thermal mass.

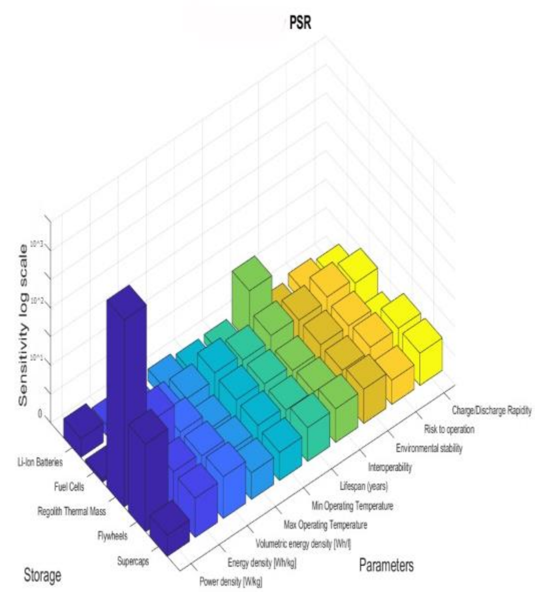

Figure 2: Suitability score gains of storage technologies to be deployed in PSRs upon unit improvement in performance.

Biospheres

The Biospheres team initiated a greenhouse design effort driven by two overarching goals: decreasing reliance on Earthbound resupplies, and maximizing scalability to ensure rapid adaptation and expansion in support of an evolving pool of potential users [8]. This required an extensive use of local resources for construction, life support and agriculture, including using regolith in substitution to - or in combination with - culture soil. The result is a modular biosphere that is designed to be semi-buried or deployed in correspondence of pits and cavities in order to improve thermal control and radiation protection, and to minimize hindrance to or harm from proximal activities. Each module can host up to ten astronauts and can be connected to four additional modules. The structure comprises a central habitat surrounded by a greenhouse, and is surmounted by a dome constituted by four separate foldable petals. When unfolded, petals expose solar arrays, thus allowing for tunable energy generation and heat management and to meet the needs of different users that might take advantage of these structures in sequence or in conjunction. A schematic representation of the biosphere is offered below. Some of the findings developed by the Biosphere team are currently being tested in the course of the ASCLEPIOS analogue mission.

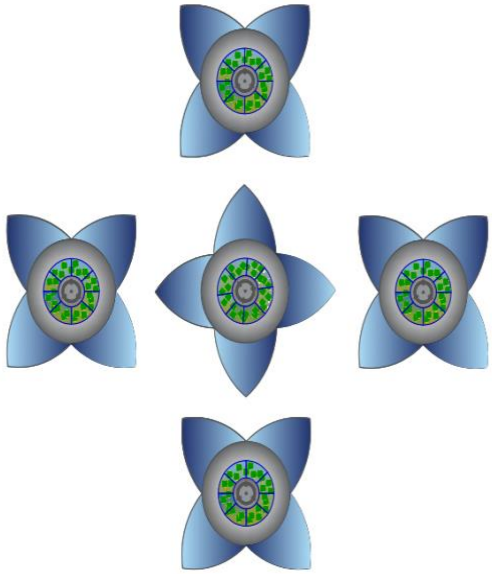

Figure 3: Biosphere modules with petal-dome opened.

Architecture and Logistics

The Architecture and Logistics team worked to assess strategic areas and activities with potential for shared or competing infrastructure and logistics among public or private actors. In order to do so, the team engaged with numerous experts within organizations involved in lunar exploration and development - such as space agencies, governmental entities and private associations - to understand stakeholder interests and drivers and to create realistic alternative scenarios to discover possible conflict points. This served as a basis to formulate an interactive workshop where representatives of stakeholders are actively involved to simulate rational actor behavior using game theory and decision science as two parties pursue their own lunar exploration campaigns in close proximity to one another. Observation of actor behavior and propagation of choices across sequences of events and interactions ultimately allows us to assess the implications of cooperative or competitive trajectories on lunar development. A first version of the workshop has been conducted during the 72nd International Astronautical Congress in Dubai, and an updated version is being developed to be rolled out in the following months.

Dust Mitigation

To facilitate the development of a shared set of infrastructure assets, the Dust Mitigation team has designed a lunar rover capable of removing dust from different surfaces while performing scientific experiments on the collected dust samples [9]. Such a mission-agnostic capability would be a great advantage offered to both new and existing players to increase the chances of success or to extend mission duration, thus making the lunar environment safer and more sustainable for all. A representation of the rover is offered in Figure below.

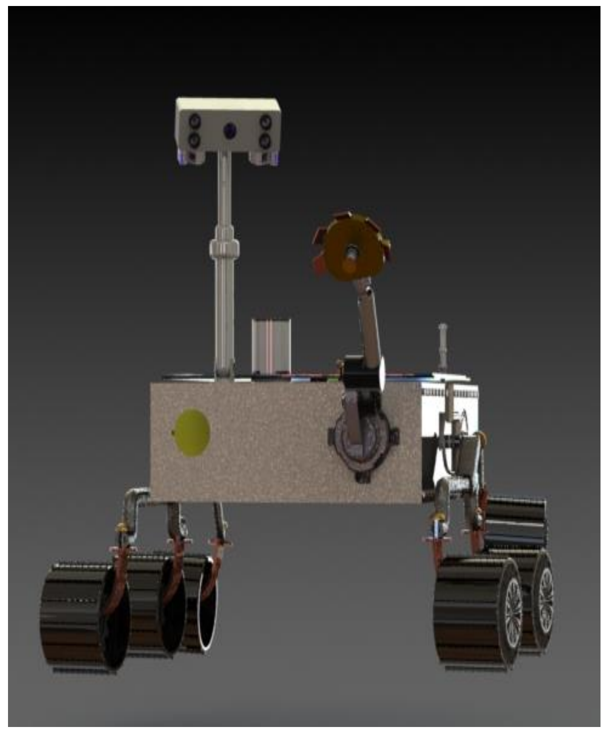

Figure 4: Dust-removing vehicle

Table 1 in the next page lists the mission goals of the rover.

Primary Goals
To remove dust from specific surfaces using a contactless system
To perform surface damage detection on the Moon
Secondary Goals
To study the production of chlorine oxides based on lunar dust separation
To perform astronomical observations from the lunar surface

Table 1: Dust-removing rover mission goals

In Situ Resources Utilization (ISRU)

The ISRU Team is currently working to design a permanently-operating lunar rover capable of autonomously mining fuel to sustain its operations uninterruptedly. Such a system could therefore provide reliable and continued support for the benefit of lunar actors offering landing assistance, telecommunication relay services, prospecting, mapping and exploration data.

Lunar Environmental Impact

The Lunar Environmental Impact team is currently scrutinizing several actors' public plans to establish a permanent presence on the Moon in order to conduct Environmental Impact Statements (EIS) on the foreseen efforts to establish continued human and robotic presence on and around the Moon. The knowledge and awareness derived from these analyses is meant to serve as a foundation for future technical and/or policy recommendations towards potential lunar codes of conduct, as well as to adapt and refine specialized tools and frameworks such as the EIS to promote long-term sustainability, global cooperation, and peaceful development.

Preliminary Conclusions from the TURTLE Group

The preliminary findings developed by the TURTLE Teams highlight the critical importance of holistic thinking for the safe and sustainable development of the Moon. To begin with landing, the incremental growth of lunar surface operations calls for the selection of internationally shared landing sites, in order to contain the harmful effects (such as dust ejection and vibrations) caused by landing and taking off. For the same reasons why an aircraft is not allowed to (normally) land on highways or fields, we must ensure that lunar spacecrafts do not disrupt nominal operations conducted on various parts of the lunar surface. The next logical step in this reasoning is the development of shared infrastructure providing essential services associated with landing and taking off. Hence why the first milestone of the LETAR baseline presented in the next section below refers to the development of lunar ports. Similar considerations can be expressed for transportation services. Moving from one area to another on the Moon presents several challenges, including but not limited to the harmful effects of dust ejection. A potential way to address these challenges would be through the identification of common pathways connecting both the various areas located inside lunar ports, as well as the lunar ports themselves to key areas of lunar operations (such as the South Pole). The importance of foundational transportation services becomes self-evident when taking a city-planning approach to lunar development. Since Roman times, the very first action undertaken to establish a city, or even just a military camp, was the realization of two streets connecting the various portions of the selected site from north to south (*cardo*) and east to west (*decumano*). Once we have clarified where to land and how to move, the next logical step would be the establishment of power stations that can support the long-term conduct of activities *in situ.* In parallel to that, it would also be useful to adopt international communication protocols as well as to implement solutions tackling the challenges posed by lunar dust. All the while always taking into account the environmental impact of our activities on celestial bodies.

Despite the clear benefits associated with the picture painted above, at present virtually every lunar mission lacks any form of holistic vision of the Moon. LETAR has been conceived to close this very gap and offer a neutral, shared reference point for the identification of key foundational elements enabling the ordered and rational establishment of critical lunar infrastructure.

2. LETAR Structure and Legal Aspects

In order to infuse the development of such infrastructure and other critical technologies with systemic and holistic thinking, a substantial paradigm switch is required [10]. Traditional roadmapping as a static activity informed by future missions and particular interests has to be complemented with a dynamic and inclusive dialogue inspired by technology-enabled goals and principles, that appeal to the broader community of all spacefaring nations. In this respect, LETAR aims to overcome the limitations of traditional roadmaps by outlining a series of overarching goals that need to be accomplished for sustainable lunar development, namely:

1. Lunar accessibility
2. Energy equity
3. Moon habitability
4. Inclusive infrastructure
5. Environmental survivability
6. Access to resources
7. Sustainable development

All the technical work produced by TURTLE as described in Sec. 2 of this manuscript ultimately traces back to these goals and principles. The combination of the findings developed by the TURTLE teams has lead to the development of the following LETAR baseline:

- Lunar accessibility can be ensured by spaceport-grade landing sites strategically located to meet the exploration and settlement interests of multiple actors and specifically developed with the capacity to safely sustain increasingly frequent landings and take-offs. Among the benefits that these lunar ports can bring, it is worth highlighting a dramatic reduction of the costs and risks traditionally associated with lunar missions.
- Energy equity can be provided by offering flexible and reliable integrated systems of power generation, distribution and storage that can scale up to tens of kilowatts of power and be deployed in regions of high interest and extreme environmental conditions. Together with standard interfaces and low enough costs of maintenance, this would enable the design of more resilient and successful missions thanks to the extended lifespan of robotic assets as well as the augmentation of their capabilities, to the benefit of financial and technological sustainability. Moreover, the lean and wide-scope quantification of the implications of technical progress outlined by the sensitivity studies conducted by TURTLE provides a first input to inform subsequent roadmapping efforts.
- Moon habitability can be concretely achieved only if lunar habitats are integrated with biospheres that can sustainably grow food, expand the habitable space through modularity, be deployed regardless of the specific environmental features, and be used by different crews. Designing such architectures to also make use of local materials and resources for construction, as already contemplated in numerous studies, would decrease the need for an otherwise unsustainable terrestrial resupply chain. Locating such biospheres within reasonable distance from spaceports would ultimately promote crew safety and turnover, and optimize water distribution in the region.
- Inclusive infrastructure is obtained as a result of a deep understanding of what types of architectures and systems are best suited to incentivize cooperation among actors. When in place, shared infrastructure would lower the barriers to access for many minor plates or non-spacefaring nations. Within such an environment, common mechanical, data, telecommunication, electrical, hydraulic or thermal interfaces will be required in order to ensure compatibility and interoperability across biospheres and habitats, landing sites and spaceports, EVA suits and electrical power systems.
- Environmental survivability is key for long-term development of the Moon. If too many missions fail because of environmental factors, massive financial and operational efforts will add up to sustain any form of continued presence. If shared assets can remove such obstacles for all players, unprecedented opportunities are disclosed to create value and enjoy the Moon and its resources. The work being proposed by the Dust removal, Biosphere and Power teams goes in this direction.

- Access to resources requires not only physical access to depots or mining sites, but also prior access to verified data and information on resources distribution and availability. In this regard, orbital probes can only paint a partial picture: ground data are required. However, probes are limited by traveling distances, lifespan and environmental conditions. A permanently operating lunar rover can overcome these issues and deliver a steady stream of data to all actors, all while testing and demonstrating critical technology for sustained in-situ resources activities in extreme environments. Plus, this knowledge would feed into the selection of landing sites and the establishment of biospheres.
- Sustainable development comes both as a result of the integration among these key building blocks, but also as a the outcome of the careful analysis of the impacts created by different missions and of the refinement of tools, best practices and technologies to prevent or mitigate such impact.

To show how TURTLE work relates to LETAR core principles, Figure 5 below provides a simplified example originating from the studies being performed by the group.

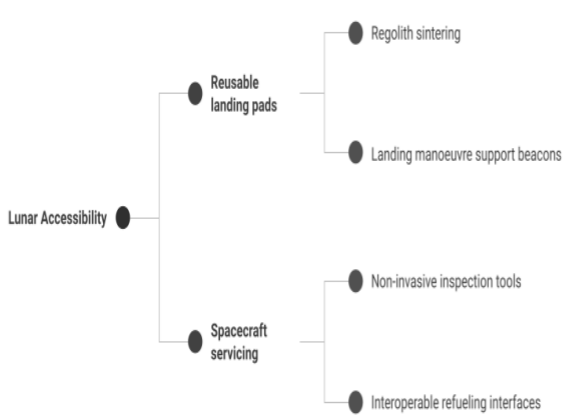

Figure 5: An example of technology road mapping informed by tech-enabled goals, in this case lunar accessibility.

Legal Status

On top of bringing technological and economic benefits, the approach proposed in the LETAR baseline would also meet the highest standards of compliance with international space law.

The most important source of international space law is the Outer Space Treaty (OST) [11]. A key provision of the Treaty is its Article IX, which ensures high-level coordination among space activities through the principles of due regard and consultation. The principle of due regard requires States to refrain from activities that would interfere with the parallel freedom of others to conduct their own operations in space. The principle of consultation prescribes that if a State has reasons to believe that one of its national space activities might cause potentially harmful interference with the activities of another State, it shall undertake appropriate international consultations before proceeding with it. These rules are based upon the legal status of space as a global common, i.e. a shared area beyond the exclusive influence of national jurisdictions, which is provided by Articles I and II OST. According to these provisions, outer space and celestial bodies are free for exploration and use in the interest and for the benefit of all Countries, and cannot be brought under the exclusive control of any actor.

The global development of a shared roadmap leading to the establishment of publicly available infrastructure for foundational lunar activities would ensure that they are conducted with due regard to the interests of all States and inherently prevent the causation of harmful interference. The collective buildup of LETAR as a tool welcoming contributions from international players at all levels of financial and technological development would also foster inclusiveness and benefit sharing in the exploration and use of the Moon by creating a cooperative lunar environment.

The efforts for the establishment of LETAR would also be an excellent way to test the suitability of the UN Long Term Sustainability Guidelines for Outer Space Activities to govern exploration and use of celestial bodies [12]. For example, the development of LETAR would allow for the "exchange of technology and equipment for space activities", in accordance with Guideline C.1. The operationalization of LETAR would also notably be in line with Guideline D.1.3, as the infrastructure suggested in its current baseline would promote the development of technologies "maximizing the reusability or repurposing of space assets" while also "encouraging the participation of developing countries" under Guideline D1.5 and "avoiding unnecessary duplication of function and efforts" in accordance with Guideline C.3.3.

3. Getting LETAR Done

A project of the magnitude of LETAR requires the development of a dedicated entity designed to manage the development and maintenance of a Lunar Exploration Technology Adaptive Roadmap - the LETAR Consortium.

The LETAR Consortium will be composed of a fixed number of managing partners and feature the participation of a variable number of contributing members. Managing partners will provide the main funding for the activities of the Consortium and will be collectively entrusted with its administration. Partners will be primarily recruited among international institutions, space agencies and companies. Contributing members will pay a membership fee and will be collectively entrusted with the development and implementation of LETAR, to which they are expected to substantively contribute with their expertise. Members will be primarily recruited among lunar operators.

The Consortium will be managed by a Board of Directors. Each managing partner will appoint a board member, and all board members will elect among themselves the Chair of the Board. The Chair will be assisted by an Executive Secretary, to be appointed by the Board under the available budget. The Board will be advised by an Expert Council, composed by representatives of the contributing members and chaired by the LETAR Manager. The LETAR Manager is a professional to be appointed by the Board at the suggestion of the Expert Council, subject to the availability of budgetary resources.

To ensure respect of intellectual property rights, LETAR will be developed in two versions: open source (LETAR OS) and limited (LETAR LTD). LETAR OS will include the technological milestones foreseen in the roadmap described in general terms, together with the number of entities working on these technologies and a rating of their importance for sustainable lunar development. LETAR LTD will show all the details of the technologies included in the roadmap and will be accessible only by managing partners and contributing members under the terms of a non-disclosure agreement.

All decisions involving LETAR LTD shall be adopted by the Board at the exclusive initiative of the Expert Council. Purely administrative decisions shall be taken by the Board at its own initiative. The recruitment of new partners shall be solely decided by the Board. The recruitment of new members is entrusted to the discretion of the Expert Council in prior consultation with the Board, which can veto acceptance if it deems it against the interests of the Consortium. Any other decision is taken by the Board in consultation with the Expert Council, at the initiative of any of the two entities.

Conclusion

The goal of this paper was to demonstrate that in order to achieve a complex goal such as planetary sustainability we need first and foremost a shift in perspective. At present, operators approach space exploration as if their missions were to happen in isolation, without factoring the impact of other activities and assuming no possibility to procure certain services *in situ*. As a result of the first deficiency, surface activities on planetary bodies will be exposed to the risk of potentially harmful interference due to the lack of information and coordination mechanisms. As a result of the second deficiency, it will be more difficult to achieve planetary sustainability due to the duplication of structures and services caused by the all-in-one design paradigm . The studies conducted by the TURTLE Group demonstrate that it is not only possible but actually desirable to overcome these limitations in favor of an integrated and holistic approach to planetary exploration. In this regard, the LETAR Baseline described above proposes the development of shared infrastructure providing essential services such as traffic management, power generation and fuel supply. To further enhance sustainability, we suggest that this infrastructure should be made of specialized, interoperable, multifunctional building blocks servicing all surface actors.

It will not be possible to achieve planetary sustainability without the organized mobilization of at least the main actors operating in key segments across the entire value chain. To enable a sustainable future of humanity on other celestial bodies, we all need to engage in a multilateral, multistakeholder process bringing together key initiatives and actors around critical aspects for the sustainable conduct of planetary activities. LETAR is meant to drive the beginning of this conversation by identifying the critical needs shared by all missions and consequently offering holistic technological solutions to address them in a safe and sustainable manner. To this end, the TURTLE teams identified critical gaps and opportunities in current technologies to be addressed at multiple levels of analysis, delineating research domains with a multitude of intersecting needs and topics that can spur further research. We therefore encourage all like-minded entities interested in this conversation to engage with us as soon as possible. The clock of planetary sustainability is ticking and we all must begin to listen and act accordingly.

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