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Lunar Mission Actor Analysis: Open Information Architecture for International Collaboration

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Abstract

Access to space is becoming more democratized, as technology development and growing competition in the launch market continue to drive down costs. The number and diversity of actors, and the scope of their activities, is growing. How the "business of the moon" will emerge from isolated missions by governments, large companies, and startups, however, remains a mystery. Through primary and secondary research, the authors of this paper categorize the variety of lunar activity in order to create a deeper understanding of the near, medium and long term components of the lunar economic landscape. Categories included in the analysis include, but are not limited to, agent type (government vs private industry vs academia, etc.), motivation, landing and operating location, credibility of the endeavor, funding models, and timing. A proposal for an open information architecture is then discussed, aiming to advance the conversation on collaborative lunar activity. With this information gathered in a regularly updated or "living" open-access framework, the authors believe all industry players and observers will be better equipped to address the opportunities and challenges in the lunar market in years to come.

Keywords: lunar economy, lunar infrastructure, lunar governance, democratizing access, open architecture

1. Introduction

Fifty years after the Apollo 11 moon landing, the global community of space actors stands again at a pivotal moment for lunar exploration and extraterrestrial civilization. Yet, these two snapshots—1969 and 2019—boast markedly different supporting ecosystems and therefore (optimistically) divergent prospects. The space exploration ecosystem in the 1970s and 1980s lacked a sustaining commercial industry; while the U.S. and U.S.S.R. made stunning technological advances to achieve lunar exploration and steady-state presence in Low Earth Orbit (LEO), the monumental cost of expanding moonwalks to moon colonies and the sheer scope of activity required for such an undertaking could not be sustained after the Cold War competitive motivation withered. Critics have long analyzed the strategic decisions that took us away from the moon [1], often with the implication that mistakes of prioritization were made (e.g. in the loss of Saturn V capability [2], or the shift to Shuttle which over-committed resources parochially [3]). An alternative reading reminds us that technologies developed ahead of their time—as the remarkable inventions of the Apollo era might be reasonably labeled—often wait in hibernation for the commercial ecosystem to catch up (e.g. the 50 year delay between the Wright Brothers' first flight in 1903 and commercial air travel in the 1950s, or the approximately 30 year wait for 3D printing to truly revolutionize the manufacturing industry despite its invention and claims to do so in the early 1980's [4]). While often jump-started with government investment and research dollars, the commercial ecosystem ultimately proves vital for the technology's self-sufficiency and growth.

From promising advancements in aerospace hardware miniaturization, to the democratization of launch providers, we are now observing the industry trends consistent with a commercial ecosystem that is "catching up." Across the space industry, we are reducing payload weight while increasing the density of computing power per dollar spent, and per kilogram [5]. Advances in rocket design and emerging tools for verifiability of lower-cost manufacturing regimes like 3D printing [6] are enabling cheaper development costs for launch systems. This technological shift, paired with more modest payloads, has spurred a revolution in agile, small launch companies that are lowering the costs to orbit [7]. The industry can now support integrators—third parties that empower new entrants to gain access to coveted launch slots with dramatically shorter wait times than what was expected just five to seven years ago. As the public "grand opening" of space draws near, the industry has begun attracting private capital—from VC funds to LLPs and sovereign wealth funds — that provide the freedom (and survival pressure) to explore grand visions that scale. While hundred-million-dollar-class missions across the most mature players are still primarily funded via large government grants and contracts, the higher risk appetite among private capital investors has broadened the scope of what is funded, advanced the pace of learning through a push for fast and reactive iteration cycles, and re-engaged the public's

interest. The response has been staggering—an explosion of new stakeholders, from newly minted space agencies throughout the developing world to high school classrooms launching annual CubeSats, has led to greater experimentation and cross-fertilization. This increase in customers, momentum behind experimentation, and growing networks of global exchange provide key ingredients for a new, sustainable market in LEO.

With this societal systems perspective on innovation and effective deployment of that innovation at scale, we must take up, as a common goal of this generation's space industry, the task of building a sustainable, multi-stakeholder ecosystem rich enough to support steady state lunar activity. Towards this goal of bolstering a multi-faceted and robust lunar ecosystem—one that can marry both competitive and cooperative models towards economic viability—we offer this lunar actor analysis. Our intent is to present a straightforward, clear accounting of the current stakeholders and their activities that are planned or underway; from this we can identify a) gaps and areas ripe for new entrants to further bolster the ecosystem and b) opportunities for cooperative and collaborative activities in overlapping interest areas (e.g. water extraction, landing pad standardization) through which we can realize more ideas with less total resources and less redundant R&D. We commend and build off of the many existing lunar ecosystem analyses; however, the short shelf life of such analyses begs the question of how we might instead develop a more dynamic, living framework with modern web tools, responsive and up-to-date to the space industry's rapid evolution. Such a tool could enable an industry-wide reference for information exchange, where clear and up-to-date access to information can entreat and empower new entrants, spur collaboration on open standards and interoperability (critical to the success of missions in resource constrained and extreme environments), and establish an efficient market where identified needs can be met through multi-stakeholder cooperative action (e.g. Gov't, NGOs, industry, et cetera). We thus take our lunar analysis one step further, geared towards the creation of an actionable open architecture for engagement in the burgeoning lunar exploration ecosystem.

2. Lunar Actor Analysis

In order to understand the influence of small and private actors on the lunar landscape, currently proposed lunar missions were analyzed and organized by expected launch year and mission type (orbiter, lander, rover), as shown in Table 1. Where possible, additional information was gathered on each mission's backing entity, primary purpose, launch vehicle and payments, funding amounts and sources, customers, landing site, and operating jurisdiction(s). These factors were chosen with the goal of highlighting how the

fledgling private sector (both large and small actors) may a) disrupt the market and ecosystem of actors, and b) diversify the focus of lunar activities from robotic science into infrastructure, services, and even civic activity.

2.1 Methodology and Research Notes

Missions were assessed for credibility according to factors such as funding, government sponsorship, major customers, secured launch contracts, and partnerships with other credible space industry actors. Missions were discussed amongst the team according to these criteria, and those assessed to have significant credibility along one or more of these axes were included as shown in Table 1 (Appendix).

One of the initial goals of this paper was to understand and illuminate missions that aimed to begin building an infrastructure on the moon that could be leveraged by future missions. To that end, missions were initially categorized as "Isolated Activity" vs. "Iterative Impact". The former designation was defined as "missions with a finite scope and a clear end of service," and the latter as "missions with plans or means to interact with other proposed or future missions in a cooperative way." However, it quickly became apparent that although many missions aim to *inform* future missions (including through sample return), all currently proposed missions fall into the "Isolated Impact" category. This finding was a principal motivating factor for developing the open architecture proposed in later sections.

2.2 Findings

2.2.1 Lunar Mission Timeline and Entities

As expected, the major current and upcoming lunar missions are predominantly government-funded and led by countries that have historically been classified as space powers including: the US, China, and the ESA, with JAXA and others being their main cooperators. Notably, Russia has not been as active in this regard. In fact, today, the United States and China are the dominant entities pursuing lunar activity through commercial, government, and public-private partnerships. Luxembourg, Korea, Germany, Austria, India, Japan and others have all expressed formal interest to varying degrees of lunar ambitions. In 2019, two separate missions attempted, but ultimately failed, in achieving a soft lunar landing: SpaceIL's Beresheet lander (an Israeli STEM project) and India's Chandrayaan-2 Vikram lander.

China is building a new human-rated spacecraft designed for lunar journeys [8]. They have announced plans for an uncrewed test flight in Q1 of 2020;

however that test relies on return to flight of the Long March 5 rocket (as does China's Chang'e 5 robotic lunar mission). It is unclear if the test of the human-rated spacecraft will be inside or outside of Earth orbit, so it may not be an actual lunar activity, but it goes to show that China is likely within space-industry error bars, if not ahead, of, the US, when it comes to engineering systems capable of sending humans to the Moon. Between that, their recent (and currently ongoing) success with the Chang'e 4 sample return mission, the Chang'e 5 mission expected to fly in 2020, and Chang'e missions 6 through 8 already announced, China is steadily and systematically advancing their capabilities towards their goal of a south pole station.

In the United States, the majority of lunar funding by dollars is going to large scale systems in support of what has become NASA's Artemis program to return humans to the Moon. NASA plans to use the Space Launch System (SLS) along with the human-rated Orion capsule to launch and deliver US astronauts, including the first female to potentially walk on the moon, to the Lunar Orbital Platform (Gateway). The Gateway will be the staging area for Project Artemis, which will consist of a set of moonwalks beginning in 2024. Beyond the Artemis program, NASA funds a diverse range of lunar activities, carefully balancing more traditional government contracts for large scale systems with commercial stimulus programs like the Commercial Lunar Payload Services (CLPS) program, NextStep, and Space Act Agreements. Furthermore, the Google Lunar XPrize (GLXP), which ended in 2018 without a winner, saw the instigation of a number of small private exploration entities, many of which continue to pursue their missions via private funding, commercial endeavors, and awards from NASA's CLPS program.

While spending by private lunar actors remains low by relative dollar amounts, these activities are the most dynamic due to their ability to capitalize on larger trends in the industry such as cost reduction, miniaturization of technology, the proliferation of actors, competition, and funding opportunities. Two particularly noteworthy players in the private industry are Astrobotic and iSpace. These companies are pursuing recurring surface activity, and have already received significant government backing to develop their own systems capable of taking commercial and government payloads as customers. In both cases, the payloads being considered range from major scientific instruments supported by government space programs, to university experiments and technology demonstrations, as well as marketing or memorabilia payloads for commercial customers.

Beyond the activities of U.S., China, and the volatile yet dynamic handful of private actors vying for an early entry into the lunar economy, the number of

credible planned activities through 2023 remains in the single digits. More ambitious private programs, such as the Blue Origin Blue Moon lunar lander and SpaceX Starship tourist flight around the moon, have set target dates for 2023 and 2024, but this is still a number of years until first flight. Overall, much of what will occur on and around the lunar surface beyond the mid-2020s is yet to be crisply determined.

2.2.2 Primary Purpose and Technology
Three main purpose and technology categories were identified in the primary analysis matrix: Orbiters, Landers, and Rovers. Orbiters are defined as missions where the primary technology developed is achieving orbit around the moon. These include tourist missions, such as SpaceX's planned #dearmoon, as well as lunar surface monitoring and staging for human surface missions. Landers are defined as missions with the primary purpose of landing and remaining at a single location on the lunar surface. Lander type missions are split between two subcategories: payload delivery, and self-contained. Payload delivery missions' main technology is to enable the safe placement of second and third party payloads on the lunar surface. Self-contained missions are those that have all the technology necessary to survive a soft landing and operate on the lunar surface. Finally, Rovers are defined as missions with the technology and purpose of landing on the lunar surface without being relegated to remain at the landing location.

As evidenced by Table 1, the majority of planned lunar missions are of the Lander variety. These missions are predominantly scientific instruments, with a small handful of truly commercial payloads. The majority of known commercial payloads are end-of-value chain services, such as ash scattering and "out of this world" marketing "selfies" with the Earth in the background. Of the more advanced missions, many have ambitions to work on or support Iterative Impact, but have yet to confirm concrete longitudinal investments necessary to extend beyond Isolated Activities. Although all the small private actors have plans for follow on missions, it is unclear the extent to which those missions are funded.

2.2.3 Mission Trends
The volatile nature of the ecosystem became readily noticeable during the analysis period as multiple missions, like those of OrbitBeyond, SpaceIL, PT Scientists and iSpace, were cancelled, crashed, went bankrupt, or consolidated into future missions by the same company, respectively.

Although the amount of private activity, government incentive programs, and private dollars provide indications that there is a renewed appetite for commercial lunar activity and the vision of

infrastructure development in support of sustained presence, there are some sobering realities highlighted by Table 1. The first is that although NASA has a major "back to the Moon" initiative, that initiative is primarily oriented towards a narrative of "bootprints"— and then on to Mars. Few of NASA's plans involve the development of utilities or infrastructure. Although its CLPS program is a leading proponent and major supporter of private commercial activity, the actual frequency of launches is not targeted at more than one every 6 months, and many of those launches are not yet funded.

The second is that these missions are landing at vastly disparate locations, so not only will they be launched far apart in time (with the notable exception of Intuitive Machines and Astrobotic both targeting July 2021 launches—though on different launch vehicles), they will also be far apart spatially (figure in Appendix B).

Together these factors highlight the chasm we still must cross to get to a point of Iterative Impact, which these authors suggest is a necessary precursor for robust development. Although there are a number of individual activities which are themselves quite credible, the existence of a true inflection point towards sustained lunar activity and eventual human presence is less obvious.

2.2.4 Additional Information and Initial Conclusions

The analysis conducted for this paper was undertaken with a specific focus on organizations that have announced a specific lunar mission. There are many instances where companies and governments have made intentions known to pursue lunar activities, however did not share the details necessary to be included in this analysis.

Ultimately, one of the key takeaways from this analysis was that the media "buzz" surrounding lunar ambitions can be misleading. The list of actors significantly outnumbers the missions proposed, as many different organizations contribute in part to a single mission. One driving factor in this is the source of the majority of funding: governments. Even when private companies are involved, government participation is almost always required, whether through formal program sponsorship (such as CLPS) or as a "customer." Until a sustainable lunar economy is developed, this will remain the case. This presents somewhat of a Catch-22, in that the realistic prospect of a genuine lunar economy is a minimum threshold for the lunar economy to be built. Ultimately, if a real market is to emerge, significant consolidation of the actor space is expected. We see the rumblings of this in the number of ex-GLXP and other small lunar actors pooling efforts to compete for NASA's CLPS awards. Many are also beginning to expect more vertical integration. One interesting indication of that

potential trend is Firefly, a launch company reportedly also building an orbital transfer vehicle and which recently reported it had acquired lander technology from SpaceIL.

One potential way forward, discussed in section 3 of this paper, is to build up information and opportunities towards collaboration between organizations, so that commitment to future lunar operations is done hand in hand, minimizing the risk of an actor being "marooned" on the moon.

3. An Open Architecture

3.1 Previous work in lunar roadmapping

To date, progress has been made in developing a set of roadmaps identifying critical technologies and scientific progress needed to enable a crewed lunar mission. Neal et al. has done significant work in gathering existing lunar mission roadmaps and mapping them to the Global Exploration Roadmap (GER) developed by 12 space agencies participating in the International Space Exploration Coordination Group. The GER "reflects a coordinated international effort to prepare for space exploration missions beginning with the International Space Station (ISS) and continuing to the lunar vicinity, the lunar surface, then on to Mars" [9].

Lunar mission roadmaps have been prepared by a variety of organizations such as the Committee on Space Research (COSPAR), the Lunar Exploration Analysis Group (LEAG), and the National Research Council (NRC). These roadmaps correlate with stated objectives in the GER. The utility of the GER, which was written at a high level, is massively increased when used in conjunction with these roadmaps, as shown by Neal et al. using the Humans to the Lunar Surface theme [10].

Evidently, disparate roadmaps developed by different types of entities are of little utility when reviewed in isolation. Mapped onto a larger roadmap, however, broader themes emerge, and a larger lunar infrastructure can be imagined.

We propose the development of an open architecture that can bring together existing roadmaps as well as illuminate efforts being undertaken by private entities, non-governmental organizations and nonprofits generally under-represented in previous roadmapping efforts. Beyond technological and scientific progress, business cases, regulatory necessities, and legal requirements will need to be elucidated going forward.

This proposed open architecture will be crucial in providing direction enabling new countries and stakeholders to join and engage in an overall effort supported by the public.

We envision an open architecture that could provide insight into the following (non-exhaustive) areas of concern in planning a lunar ecosystem:

- Where is industry active? What are they relying on government to provide?
- Where is the government active? What are they hoping to enable?
- How will NGOs factor into the ecosystem?
- Which countries are represented, and at which levels? Private or public?
- Which aspects of the ecosystem are mission-critical? Who is providing these services and what stage of development have they reached?
- What is the proposed timeline, and what is our adapted timeline?
- What are the core limiting reactants and gatekeeper technologies, and which actors are addressing these issues?
- Where are the opportunities for shared investment, shared risk, or early customer commitment?
- Where are the opportunities for shared standards which reduce the cost and risk of interactions, and shared technology that reduce the cost of new entrants?

Such a roadmap would not only accelerate collaboration and illuminate actor involvement in various fields, it would reveal assumptions regarding the expected role of governments, non-profits, and corporations in a lunar ecosystem.

The current lack of such an open architecture means that all actors must assume a certain amount of risk related to the uncertainty of actions of other actors in the ecosystem. Development of an open architecture could have the potential to enable industry to identify plans already under development, allow government to enable development of proposed industry activities, and provide a healthy, attractive environment defined by collaboration rather than low-information or opaque competition.

3.2 Lessons learned from the International Space Station

Although a full treatment of potential analogs for increased lunar activity is beyond the scope of this paper, one historical precursor to proposed crewed lunar missions is the development of the International Space Station (ISS). Both efforts are capital-intensive, multinational, multiyear, multi-stakeholder projects that rely on overcoming significant engineering, science, and regulatory challenges. The successes and pitfalls of the development of the ISS provide a case study for our proposed open architecture for lunar missions.

Through collaboration and agreement regarding certain international standards, the ISS was able to leverage the efforts of many nations during its development. Standardization of interfaces and habitation systems allow astronauts from various nations to train at shared facilities and use shared technologies to complete mission objectives. Smaller nations can rely on larger nations for knowledge-sharing (i.e. training and deployment of first UAE astronaut). Once infrastructures are built, commercial entities can license and build on those technologies creating valuable business propositions offering benefits to the larger public (i.e. NanoRacks or SpaceX).

For all of its success, however, the ISS was bogged down by high mission costs and significant deviation from the initial proposed timeline for construction. The cause of these issues has been examined extensively in the literature. Major roadblocks for the project have been identified, such as failed technology transfer mechanisms, lack of central management, and political instability.

Many of the investments made by NASA could have been maximized or avoided by linking up with industry or international partners in the development phase. Rather than pursuing shared objectives, NASA created plans of actions that, after further development, required international and commercial partners to justify and fund (i.e. the ISS). If NASA and other large agencies are more collaborative and can also monitor industry activity, they can make smart investments, building infrastructures and programs such as the COTS program that will incentivize industry to develop technologies that will have a significant multiplier effect across the entire space (in this case, lunar) ecosystem. Major roadblocks to collaboration came by way of a failed technology transfer mechanism, causing serious delays and national security concerns during the early years of the project [11].

The ISS established a promising model for international collaboration through the development of legal norms established via interstate and interagency agreements: the Intergovernmental Agreement (IGA) between the participating governments concerning cooperation on the International Space Station; a number of bilateral Memoranda of Understanding (MOU) between the space agencies of the partner states— ESA, RSA, NASA, CSA and JAXA; and several bilateral agreements taken on between active members to implement the MOUs. These regulated technical issues of immediate cooperation and coordination in developing ISS elements, their delivery and assembly in orbit, crew training, the mechanisms of interaction of the cooperating agencies in solving issues under dispute, and other matters defining the rights and obligations of the international crew in and on the station [12].

Taking the step from LEO to the moon will be much more costly, involve more diverse actors, and the harsh environment (e.g. radiation, lunar dust, greater

temporal and spatial distance from Earth resupply and rescue) will pose serious risks for the astronauts and technologies involved. The development of an open architecture would be a valuable instrument to manage and mitigate these risks.

Additionally, while the ISS remains a scientific outpost managed by governments, most visions for the Moon involve the emergence, over time, of a "village" type approach. Such a Moon Village would involve a multi-stakeholder ecosystem involving government, commercial, and civil actors [13]. In an environment where coordination is not centrally controlled, this greatly increases the importance and value of an openly accessible architecture that can be dynamically updated for all actors.

3.3 Comparison of existing roadmaps in their treatment of In-Situ Resource Utilization

To understand the scope of existing roadmaps, and where a Lunar Open Architecture would be useful, four roadmaps were examined and compared, using In-Situ Resource Utilization as a case study. The four roadmaps considered were: the NASA Technology Roadmaps, developed by NASA's Office of the Chief Technologist to identify needed technology candidates and development pathways that align with NASA's strategy for the next 20 years; the Lunar Exploration Analysis Group Roadmap, developed by a group of industry players and scientists from public research institutions to lay out an "integrated and sustainable plan for lunar exploration"; the Global Exploration Roadmap, developed by 14 space agencies with the intention of "expand[ing] human presence into the Solar System, with the surface of Mars as a common driving goal"; and the European Space Agency's (ESA) Space Resources Strategy, particularly helpful in the ISRU example.

3.3.1 NASA Technology Roadmaps

The NASA Technology Roadmaps were published in 2015, and are used as part of the agency's technology portfolio management process to prioritize technologies that benefit NASA and the Nation, as documented by the Strategic Space Technology Investment Plan.

The roadmap is divided into 15 Level 1 "Technology Areas", broken down into Level 2 Technology Areas, which are subsequently broken down into sub-goals enabled by distinct technologies. In-Situ Resource Utilization (7.1) is a Level 2 categorization, categorized under Technology Area 7, Human Exploration Destination Systems. The goal of ISRU is defined as "leveraging in-situ resources to dramatically reduce launch mass and cost of human exploration missions." There are four sub-goals associated with ISRU, which are analyzed with respect to objectives,

challenges, and benefits as well as the associated technologies needed to enable the sub-goal.

For some technologies, capability and technology needs are identified. These needs are assessed through associated parameters for state-of-the art performance goals, and, for the technology needs, a technology readiness level.

The timeline for technology development is driven by NASA mission timelines, and prioritized according to whether the technology is mission "enabling" or "enhancing". For example, for the Lunar Crewed Mission, set to launch in 2027, ISRU is seen as a mission-enabling Technology Area. TechPort is an online portal that categorizes investments in technology using the taxonomy defined by the roadmaps.

3.3.2 Lunar Exploration Analysis Group Lunar Exploration Roadmap (LEAG-LER)

While the NASA Technology Roadmaps are driven by categorizations of technologies, and prioritized with regards to NASA Mission Objectives and timelines, the LEAG-LER roadmap is intended to lay out an integrated and sustainable plan for lunar exploration, allowing "NASA to transition from the Moon to Mars (and beyond) without abandoning the lunar assets built up using taxpayer dollars." The LEAG-LER roadmap makes specific reference to enabling international cooperation as well as commercial development through "early identification of 'commercial on ramps' that will create wealth and jobs to offset the initial investment of the taxpayer." Organized by "themes", the goal of the roadmap is specifically for lunar exploration in service of pursuing scientific activities (Science 'Sci' Theme), using the Moon to prepare for other future missions (Feed Forward 'FF' Theme), and extending sustained human presence with the goal of eventually establishing a settlement (Sustainability 'Sust' Theme).

Each theme is comprised of goals, which are comprised of objectives. Each objective is analyzed with regards to timeline, prioritization, rationale, and specific initiatives needed to achieve the objective. The timeline indicates what level of development will be needed at each step of lunar exploration. Early exploration consists of robotic precursors and the second human landing; middle exploration is the initial outpost build-up including stays of one lunar day and part of the lunar night with additional Robotic missions; and the late stage is when the lunar outpost has been established with expected stays of >30 days and Robotic missions. Objectives are prioritized by low, medium, or high priority. Low priority objectives would be beneficial, but not essential, or could be conducted more efficiently elsewhere; medium priority objectives could be enabled with sufficient infrastructure investment; and high priority objectives are essential to make progress in habitat or exploration development.

In the ISRU example, a sample objective is the "Establishment of in-situ production of life-support, power system reagents, propellants and related resources." The analysis for time phasing points to, at the "late stage", "utiliz[ing] locally produced oxygen, water and fuel to eliminate logistics supply of consumables from Earth."

3.3.3 The Global Exploration Roadmap and ESA Resource Strategy

The Global Exploration Roadmap (GER) and ESA Resource Strategy are both examples of documents developed by agency organizations with the intent of involving other sectors (such as the commercial industry or science community) while aligning on mission priorities with multiple stakeholders. In the case of the GER, 14 agencies were involved in the creation of the roadmap, while ESA is comprised of 22 member states itself. These roadmaps are useful examples of creating forums where stakeholders across nations can come together to exchange information while aligning and coordinating strategies in order to maximize benefits for all members. Unlike the previous roadmaps (LEAG-LER and NASA Technology Roadmaps), these documents are static PDFs, which are not organized by technology areas or objectives. Instead, they offer general guidance or timelines with regards to shared interests among member parties. These roadmaps are much less in-depth or detail, but still may list technology "gaps", or identify areas of specific strategic investment.

The GER is periodically updated (it is currently on the 3rd edition), and allows countries to define and coordinate mission timelines, coming together to build upon architecture from other countries, or pursue collective objectives. In the case of ISRU, the roadmap lists technology gaps that need to be addressed to enable resource acquisition and use, including: liquid oxygen and methane propulsion technologies, dust mitigation technologies, autonomous systems, and tele-robotic operations with time delay. They also, however, identify partnerships as a key enabler of the industry, pointing to strengthening ties with industry to facilitate closing knowledge gaps.

In the case of the ESA Space Resources Strategy (SRS), the document is part of a larger suite of strategic plans developed by the agency. The aim of the SRS is to solidify ESA's "position as a leader and an enabler for European science and industry" ensuring the region will play a critical role in the utilization of resources in space, "while delivering social and economic benefits in the near term here on Earth." The strategy itself is organized by strategic drivers, objectives, and specific priorities and outcomes to be achieved by 2030. While some enabling technologies are identified, the focus of the document is in proposing a general timeline by which crucial architectures need to be achieved that could "unlock" the potential benefits of space resources.

For the ISRU example, a stated priority is "establishing the resource potential of volatiles at the poles and regolith and pyroclastic deposits across the lunar surface", with associated outcomes expected by 2030: "identification and characterization of at least one non-polar deposit and one deposit of polar ice."

In summary, these four roadmaps provide primarily overlapping information with a few, notable distinct contributions, and at times an approach uniquely tuned to strategic interests by geography (e.g. US, Europe). See Appendix C for summarized conclusions across these four roadmap examples. We note an opportunity to merge the impactful information contained within related roadmaps to both a) reduce redundancy and b) surface common, shared perspectives towards actionable lunar progress. Our proposal for an Open Architecture also aims to transform the static information and "snapshot" nature of these roadmaps into a "living" framework, representative of the rapidly evolving space industry.

3.4 Proposed structure for a Lunar Open Architecture

Today, we are connected to the Internet even in the furthest reaches of the globe (never mind the ISS) 24-7, and our phones contain chips more powerful than the Apollo computers. We use real-time collaboration technology to manage even the most mundane activities such as grocery lists. Yet roadmaps for lunar exploration and settlement, one of the most advanced technology projects of our species, are still produced and managed in PDF format, updated on 5 or 10 year timeframes. Today, the entire space industry shifts more quickly than this. This has a real impact on the currency of these plans, and their utility for coordination, planning and investment.

An "open" approach to Lunar architectures and roadmapping would contain a living, dynamic, and up-to-date information portal. This portal would track stakeholders, engineering efforts, science, and coordination and regulatory efforts. It would name, identify, and track the constituent pieces of the "Lunar Challenge" writ-large (from launch, to landing, roving, resource identification, and habitation, etc.), in a modern database system which is editable, linkable, and online.

The open architecture would also have an institutional framework for participation, with transparent mechanisms for submitting updates, named actors, and a process for recognizing credible actors and contributions. It would contain a framework for community input on next steps, identification of gaps, and overarching goals (for many of which, we should expect diverging opinions). Through tracking the state of the ecosystem, an open architecture would also support cooperation through identifying projects for shared

undertaking, as well as surfacing complementary foci and differing perspectives.

Using modern web technology, an open architecture would be able to incorporate new information from decadal surveys and static roadmaps, while also soliciting input from diverse private actors, or those with smaller footprints, and those less likely to be in a position to contribute to or directly influence the space agency roadmaps. Finally, technology could also support the development of advanced features such as elements of anonymity, existence proofs, and graded access to the specifics of proprietary plans. It could, if desired, scrape public, online systems for permits, launches, and patents, to autonomously maintain current status across many stakeholders that may not always reliably self-report.

Building on the lessons learned from the ISS, the many years of roadmap development, and the motivations laid out above, there are a number of modern institutional examples on which an Open Architecture project could build. These include:

- The Internet Engineering Task Force (IETF), an open participatory body which develops protocols used on the Internet;
- The Worldwide Web Consortium (W3C), a standards body focused on interoperability and building an open tech stack;
- CERN, which has an explicit international governance model, and involved a collaborative architecture for co-construction, shared financial responsibility, and a massive open data project;
- The Open Stack Foundation, an open source software consortium with a central core of capability chosen by sustaining members, built on, by, and for commercial and non-profit activities alike.
- Nascent attempts to co-develop Artificial Intelligence algorithms, models and coordination mechanisms, such as Open AI.

Ultimately, the design and implementation of an open architecture will involve a consultative process with stakeholders, as well as light weight web technology prototypes and experiments. These experiments will impact whether the open architecture project prioritizes, for example, information architecture, distribution, coordination, or active policy-making features. It will also inform the architectures of engagement and incentives for participation. There have been some prototypes in this direction by projects such as Space Fund and Lunarpedia. The authors are currently exploring the use of a participatory web platform known as PubPub (pubpub.org); we actively invite collaboration and an open-source process for requirements drafting. These excellent resources demonstrate some of the exciting possibilities of modern web-enabled data sources.

The authors believe that the contents of agency and inter-agency roadmaps, combined with the capabilities of modern web resources, with new layers of participation and facilitation, can knit together into a new resource that has the possibility of truly accelerating lunar progress.

4. Conclusion

Since the last mission to the moon and the renewed interest in making a return, much has changed in the landscape of the space industry. Now, governments from around the world have developed capacities for undertaking their own missions and commercial players have become a crucial piece of the ecosystem.

Thus far, however, despite the emergence of "global" strategic plans and roadmaps, a cohesive lunar strategy has yet to be fully elucidated. Our analysis shows the current state of lunar actors, including stakeholders and planned or ongoing activities, and highlights the lack of coordination amongst these actors. This lack of coordination is seen in almost all aspects of the lunar ecosystem. Missions undertaken to-date have been physically disparate, with missions being conducted on opposite hemispheres of the lunar surface, with very little planned interaction. There has also been very little development in infrastructure, or attempts to build upon past missions, even within agencies undertaking multiple missions to the moon.

Nearly all commercial players are still reliant on government contracts and commercial payloads are largely unsustainable, with few offerings showing concrete commitment towards developing an interdependent lunar ecosystem. Furthermore, the actual volume and nature of lunar activities is not as extensive or "commercial" as previously characterized. Actual mission frequency as examined in the past few years has been quite low (approximately one mission every six months), but can be misconstrued as more extensive due to the various components that contribute to the mission that are highly publicized.

Enabling a future lunar ecosystem will require much more coordination amongst all players and a steady cadence of infrastructure development. A first step towards developing an ecosystem and mechanisms for increasing cooperation is the tool we propose: a living open architecture for engagement in the burgeoning lunar exploration ecosystem. This framework can serve as an industry-wide model for information exchange, empowering new entrants, spurring collaboration, and initiating the development of open standards and methods for interoperability between lunar actors. A robust return to the moon will require a high level of coordinated planning and understanding from all actors that are meant to contribute to, and occupy, the new lunar ecosystem.
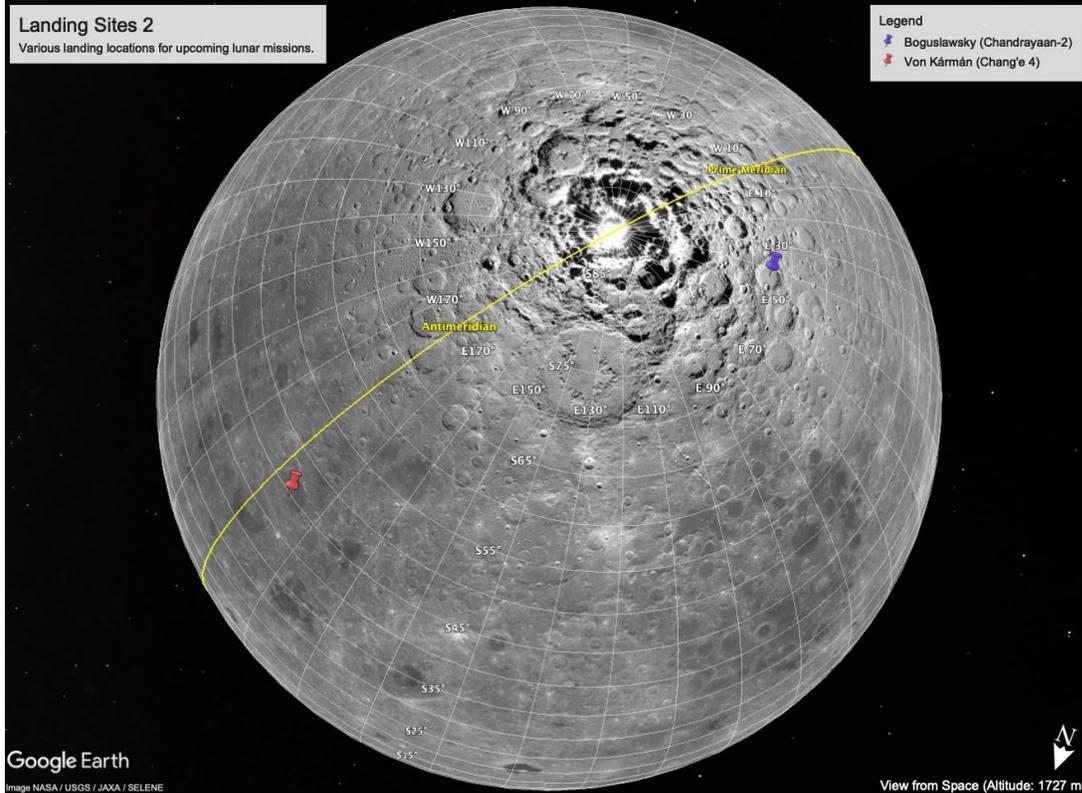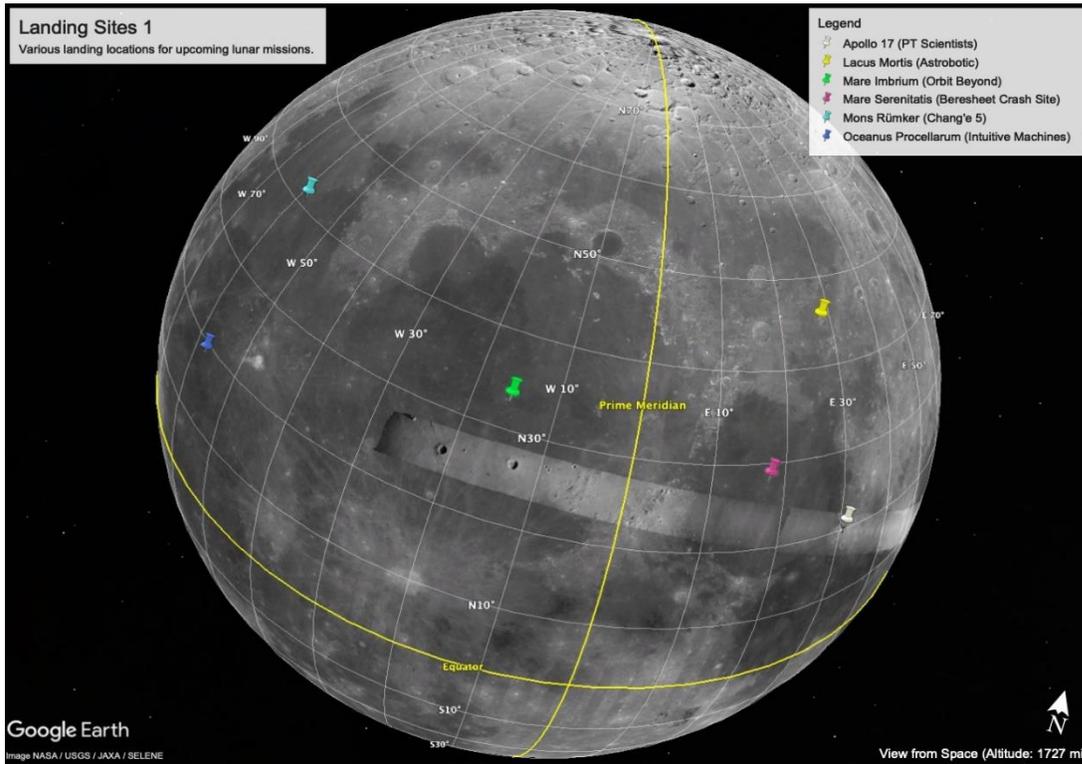
Appendix A
(Table 1: Lunar Actor Matrix)

2019	April	September	December
Launch Vehicle	SpaceX Falcon 9	GSLV Mk III	Long March
Orbiter			
Lander	*Crashed* Beresheet Lander	*Crashed* Vikram Lander	Chang'e 5 Sample Return Mission (expect delay to 2020)
Rover		*Crashed* Pragyan Rover	

2020	July	September	December
Launch Vehicle		Rocket Lab Photon (first mission)	
Orbiter		*Cancelled* iSpace Orbiter	NASA CAPSTONE testing gateway orbit
Lander	Moon Express (tentative)	*Cancelled* Orbit Beyond Lander (CLPS)	
Rover			

2021	July	September
Launch Vehicle	SpaceX Falcon 9 / ULA Vulcan	SpaceX Falcon 9
Orbiter		
Lander	Intuitive Machines Nova C Lander / Astrobotic Peregrine Lander	iSpace Lander
Rover		

2022-2024	2022	2023	2024
Launch Vehicle	SpaceX Falcon 9	Blue Origin New Glenn / SpaceX Starship	SLS (tentative, still pending date announcement)
Orbiter	Korea Pathfinder Lunar Orbiter	SpaceX #dearMoon (crewed flyby)	Orion (tentative, still pending date announcement)
Lander			Blue Origin Blue Moon Lander
Rover		iSpace Rover	

Appendix B
(Proposed Lunar Mission Landing Locations)

Appendix C
(Conclusions across Roadmap Analysis)

	NASA Technology Roadmaps	LEAG-LER	Global Exploration Roadmap	ESA Space Resources Strategy
Industry Involvement in Development	General move to public/private partnership model	X	*Stated that industry is considered, but not involved in process*	*Stated objective of enabling industry*
Science Objectives	Applied research	X	X	X
Technology Objectives	X	X	X	X
Policy Objectives in support of S+E		X	X	X
Survey of existing actors			To some extent, an overview of member agency activities	
Last Update/Frequency of Updates	2015/ Revision process underway for 2020 NASA Technology Taxonomy	Updated/modified as "data becomes available"	Currently on the third edition, updated 2018	2019/none stated
Format and Structure	PDF + associated TechPort	PDF	PDF + one updated website for lunar volatiles	PDF

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