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► To cite this version:

Paolo Guardabasso, Simone Paternostro, Pablo Bedialauneta, Romain Fonteyne. Lunar landing necessary building blocks and good practices for a sustainable development of human lunar activities. *Acta Astronautica*, 2023, 202, pp.782-790. 10.1016/j.actaastro.2022.10.025 . hal-03975092

HAL Id: hal-03975092

<https://hal.science/hal-03975092v1>

Submitted on 6 Feb 2023

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Lunar landing necessary building blocks and good practices for a sustainable development of human lunar activities

Paolo Guardabasso^a, Simone Paternostro^{b,*}, Pablo Bedialauneta^c, Romain Fonteyne^d

^a ISAE-SUPAERO, 10 Avenue Edouard Belin, Toulouse, 31055, France

^b Telespazio Belgium, Huygensstraat 34, Noordwijk, 2201 DK, Netherlands

^c Airbus Defence and Space, Avda de Aragon 404, Madrid, 28022, Spain

^d European Space Agency, Keplerlaan 1, Noordwijk, 2201 AZ, Netherlands

ABSTRACT

Keywords:

Human space exploration roadmap
Sustainable Moon exploitation
Landing site
Moon settlement
Lunar spaceport

After almost 50 years from the last step on the Moon in 1972, Space Agencies and companies from all over the World are evaluating once again the need, potential, and benefits of human settlements on the Moon and beyond. Several spacecraft, landers, and rovers have already made their way on Earth's only natural satellite, and more will come in the coming years, followed by or in parallel with human missions, with all the related challenges and issues to overcome. At first, Human activities will target specific locations on the lunar surface, mainly driven by scientific objectives. For these missions, the landing site will necessarily be close to the target areas until a surface transport infrastructure is put in place, such as a system of transport rovers or a rail network. As the interest and involvement of public and private actors grow, and depending on their mission objectives, we will see either massive landings with multiple spacecraft involved or specific pinpointed landings with relatively small assets, to perform local analyses without the need to bring a full settlement to the location. Therefore, it is fundamental to see which resources/terrain characteristics will act as an attractor for intensive human activities with multiple landings that will need traffic management regulations. One of the objectives of our research is to analyze those potential attractors and identify key factors that would make specific locations of the Moon more suitable for landing (e.g. surface characteristics, distance from points of interest). Once defined, the following objective is to evaluate what features and services a landing site should have in order to support exploration or exploitation missions and become an efficient spaceport. In parallel, as mentioned above, all these activities on and around the Moon's surface need to be regulated and coordinated to avoid a "far west" scenario, with the related potential hazards that could affect the lunar environment, human settlements, and facilities. The last objective of our project is to evaluate and propose ideas on how future missions could be regulated, taking into account that the Moon is a different celestial body that, at the current moment, is not under any national or international significant traffic management regulation. The present abstract is submitted under the auspices of Space Generation Advisory Council (SGAC) Technical Unit Research for a Thriving Lunar Ecosystem (TURTLE).

1. Introduction

With the first maiden flight of the Orion capsule in 2022, the Global Exploration Roadmap (GER) is about to reach a new milestone [1]. Almost 50 years after the return of the last Apollo crew from the lunar surface, the Artemis program is a promising international collaboration that has defined a new era of space exploration with a two-fold objective: to allow astronauts from multiple continents to step foot on the lunar surface once again, and support the construction of lunar settlements in preparation for the exploration of Mars. For the last 20 years, space agencies have focused on Low Earth Orbit (LEO)

crewed missions to the International Space Station (ISS), endeavoring to establish a sustainable human space program to go back to the Moon. Now, with new collaborations and accords being signed, the return to the Moon is more than likely to happen in the coming decade.

This new enthusiasm toward the exploration of the Moon comes with a cost: the diversification of the space actors and the densification of the space traffic [2]. The first phenomenon implies that an increasingly larger number of entities, both public (such as national agencies) and private (both established firms with large space heritage and emerging companies), will want to be involved in the new market,

* Corresponding author.

E-mail address: paternostro.simone@hotmail.com (S. Paternostro).

Nomenclature

SGAC	Space Generation Advisory Council
TURTLE	Technical Unit Research for a Thriving Lunar Ecosystem
CLEP	Chinas Lunar Exploration Program
CLPS	Commercial Lunar Payload Services
COPUOS	Committee on the Peaceful Uses of Outer Space
CSA	Canadian Space Agency
DEM	Digital Elevation Model
EAGLE	Effective and Adaptive Governance for a Lunar Ecosystem
EOL	End Of Life
ESA	European Space Agency
GER	Global Exploration Roadmap
GNC	Guidance Navigation and Control
IAC	International Astronautical Congress
ICAO	International Civil Aviation Organisation
ISRU	In Situ Resources Utilisation
ISS	International Space Station
JAXA	Japan Aerospace eXploration Agency
JPL	Jet Propulsion Laboratory
LEAG	Lunar Exploration Analysis Group
LEO	Low Earth Orbit
LOLA	Lunar Orbiter Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
PSR	Permanently Shadowed Region
S/C	Spacecraft
SLS	Space Launch System
SP	South Pole
SSA	Space Situational Awareness
STM	Space Traffic Management
VIPER	Volatiles Investigating Polar Exploration Rover

fueling *de facto* its growth. The second, a more natural aspect that directly stems from the first one, implies that a significant number of launches will be dedicated to beyond-Earth destinations in the coming years.

While looking from the point of view of landing operations, it becomes clear that enforcing traffic regulations on the lunar surface, as well as on the access to its assets (*e.g.*, resources, areas of scientific interest, regions of interest, historical locations), must be taken very seriously to potentially avoid a disastrous scenario. It is of paramount importance to prevent this by acting early, before traffic increases, to foster cooperation in the creation of a set of recommendations, in its first and simplest outcome, up to establishing Space Traffic Management (STM) rules and unified standard interfaces for the decades to come.

1.1. Problematic

Future human activity on the Moon will have an impact on the lunar surface and orbital ecosystem. Therefore, the risk of initiating and perpetrating activities that are not sustainable in the long term should be reduced as much as possible through coordination and collaboration. A pessimistic future, one where an agreement was not met between the different actors, might potentially mean that a “far west” scenario

develops, where increasing unregulated landings, in turn, escalate the risk for incidents/collisions.

Moreover, several years of intense human activities without regulation are likely to change the surface features of the Moon, threatening resources and scientific sites with propulsion plumes, and polluting the lunar “atmosphere” as well as its surface with exhaust gases. Simulations show that rocket exhaust vapor can quickly disperse all over the Moon, and 30%–40% can persist in the lunar atmosphere and surface for up to two months [3]. For instance, the scientific community has recently raised concerns about the influence of future extraction operations on the purity of lunar samples [4]. Finally, the accumulation of debris and depleted stages on the surface will probably pose a problem, especially if waste management or repurposing cycles are not put in place.

The failure to determine a plan to exploit the Moon and its resources in a sustainable way is likely to jeopardize its access for future generations. Preventing these scenarios, instead of searching for a remedy afterward, involves focusing early on activities such as:

- researching future targets and points of interest on the surface of the Moon, selecting main areas to focus on for regulation;
- focusing on the design of future landing sites, searching for the best combinations of services to be provided in the direction of a sustainable lunar spaceport;
- studying potential scenarios of future traffic toward the lunar surface and draft a regulation plan.

Moreover, focused studies on the effect of landing operations on the lunar ecosystem such as those by Metzger [5] would help to better understand the influence of human activities.

The list is far from complete, but these steps, if taken early enough, would surely benefit the understanding of the effective sustainability of lunar activities as they are planned now, and a way to improve them toward a more durable human exploration of space.

1.2. Contents of this paper

Therefore, this paper aims at contributing to the investigation of these problems. After an introduction to human activities on the Moon in Section 2, Section 3 focuses on identifying potential criteria that will drive the choice and design of future landing sites. Then, the main elements included in the preliminary design of a lunar spaceport site are presented in Section 4. Potential recommendations and strategies are thus reported in Section 5 for an optimum regulation and coordination of spacecraft for the far-fetched future, before providing some general conclusions about the work in Section 6.

2. Future human activity on the Moon

2.1. Next missions and locations

The necessity to have an international agreement on STM will surely become clearer with the consecutive Artemis missions to the lunar surface. Indeed, the program operated by the National Aeronautics and Space Administration (NASA) is expected to start with Artemis 1 and its uncrewed test flight in the second half of 2022. However, the first crewed flights are expected for 2024, with the objective to test the Orion capsule atop the American Space Launch System (SLS). From there, numerous crewed missions may be expected for the next years – from public or governmental agencies, but also from private ones – to start permanent lunar bases. In this regard, the Artemis program highly differs from Apollo. As a result, one must identify the key elements and their correlated objectives for a successful return to the lunar surface.

2.2. Lunar magnets

Future operations to the Moon will be attracted by elements or properties with favorable characteristics or uses. Areas of the Moon with desirable conditions or resources will see more activity than other areas that do not present these advantages. In this study, these factors of interest are denominated as “magnets”. Several of these can be identified. In this work, they are divided between natural resources, geological features, and previous missions’ assets.

Among natural resources, water surely has the spotlight at the current time [6,7], and it is clear how metals, rare-Earths, Oxygen, volatiles, and radioactive materials will play a significant role [8], once the first settlements are established on the surface. Illumination (for solar power and thermal control) and Earth communication (line-of-sight) can also be considered natural resources to target the abundance of.

Geological features help identify locations suitable for future missions, including Permanently Shadowed Regions (PSRs), but also points of “eternal” light for solar farms, or canyons, lava tubes [9], and craters for the construction of habitats and spaceports.

Another potential magnet for future missions will be represented by previous missions, to be visited for scientific reasons, or as a tourist attraction.

2.3. Objectives

Missions toward the Moon will be as varied as complex. Nevertheless, four macro-objectives have been identified concerning the magnets previously discussed: science, resources, services, and demonstration.

The first objective includes all the missions aimed at studying the history of the Moon, performing astronomy observations and space environment measurements, and monitoring human physiology and biological processes on other celestial bodies. Studying, collecting, and utilizing the resources present on the surface of the Moon to use them and/or make a profit will become central, with the production of rocket propellant, construction materials, and potentially rare substances to be exported to Earth; tourism is considered as an exploitation of resources as well. Services will be needed by all other missions, including support to researchers/workers/tourists, mobility on the lunar surface, and the necessary transportation infrastructure between the lunar space and surface. Finally, while demonstration missions will be the ones with a lesser impact on the lunar environment, they will be key for testing new equipment, In Situ Resources Utilisation (ISRU) techniques, propulsion systems, and surface mobility, to name a few. They are key to all other objectives and are more likely to happen first.

2.4. Mission scales

Future space missions will likely imply several spacecraft. Nevertheless, from the standpoint of landing operations, the interest lies in identifying mission categories and the respective scale (intended as an overall size/mass of the spacecraft involved). Four different scales are identified: robotic exploration with small automated or teleoperated vehicles with masses in the order of 1 ton; robotic heavy cargo, uncrewed vehicles with significantly higher masses (~ 100 tons) to transport payload to and from the surface; crew scientific “sortie” missions, intended as expeditions targeting a specific location, such as the Apollo missions, with masses of ~ 10 tons; crew heavy transport vehicles with the capability to transport several crew members to surface settlements, and a mass of ~ 100 tons.

In Table 1, mission scales are put in relationship with the potential mission high-level objectives. On the one hand, robotic exploration spacecraft will be used for scientific and technological demonstration missions and will land in pinpointed locations across the Moon. On the other hand, robotic heavy cargo missions will likely land close to future or actual settlements, bringing massive equipment for resource

Table 1
Relationship between mission scales and mission objectives.

		Objective			
		Science	Resources	Services	Tech. Dem.
Mission scale	Robotic exploration	✓	✗	✗	✓
	Robotic heavy cargo	✗	✓	✓	✓
	Crew scientific sortie	✓	✗	≈	✓
	Crew heavy transport	✗	≈	✓	✗

exploitation and support systems. Crew scientific missions will be targeted to specific objectives on the surface. Finally, crew heavy transport vehicles will have to land close to the established settlements, bringing several people to the surface of the Moon.

3. Landing site selection criteria

Past and current lunar exploration plans have, in general, scientific return as their major focus. In fact, humans are still in the phase of characterizing the celestial body, rather than establishing a presence on it and actively using its resources. Technological development and demonstration missions are also increasingly of interest.

The main objective in the selection of sites for NASA’s Apollo landing crews was targeting areas that would be as much variegated as possible, to maximize the scientific return of sample collection [10]. In more modern times, taking the example of an active and fast-paced series of lunar missions, the China’s Lunar Exploration Program (CLEP) proposed a selection of landing sites based on scientific criteria [11], to which engineering constraints are later applied, also considering the heritage gained with previous missions. Other entities, such as the European Space Agency (ESA) and the Lunar Exploration Analysis Group (LEAG), released reports detailing the near-future objectives to be targeted by lunar missions, focused mainly on the characterization of the lunar surface environment [12,13]. Coming missions, such as the Volatiles Investigating Polar Exploration Rover (VIPER) rover, which is part of the Commercial Lunar Payload Services (CLPS) from NASA, will be the first rover to fully focus on mapping *in loco* the water resources at the lunar south pole [14].

3.1. Figures of merit for selection

This work mainly discusses the future of lunar exploration, in a scenario where the focus will be inclined to shift toward a lunar permanent establishment and exploitation. Resources available at a location will then likely become a key driver for landing site selections for long-term human settlements, as ISRU techniques for building and producing products on the lunar surface will evolve. In the continuation of their scientific interest demonstrated for lunar missions such as Luna 25 [15], Luna 26, and Luna 27, geological features will play a significant role in site selections as well: the craters, canyons, terrain slope, and a site’s navigability are characteristics that contribute largely to its selection.

The mentioned studies discuss the landing site selection for lunar missions but are prone to defining the appropriate locations based on a need at a certain time period. However, depending on the timescale, priorities might shift from one factor to another. Consequently, the parameters that could characterize a landing site selection and help with traffic management vary depending on the scenario. Based on the GER objectives, three main scenarios can be described as follows:

- Settlements not yet in place
- Settlements have been in place for less than 30 years
- Settlements have been in place for more than 30 years

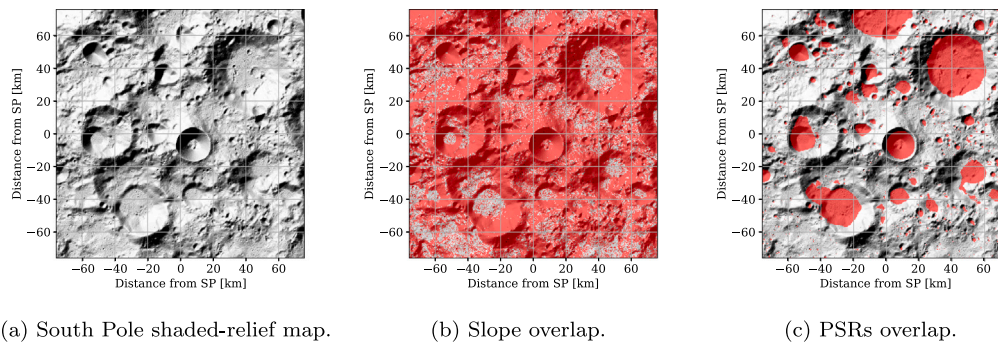


Fig. 1. Lunar topography analysis intermediate maps on a 152×152 km grid. Resolution of 240 m/px, centered in the lunar South Pole (SP).

For each of these scenarios, several predefined parameters have been considered dominant in the landing site selection, referred to as landing site criteria thereafter.

These parameters include:

- **Resources** – Amount of resources possibly available near the selected landing site, including water ice, hydrogen, as well as other volatiles with scientific value.
- **Communications and Coverage** – Coverage of end-to-end communication with Earth from the landing site.
- **Topography of the lunar surface** – Main characteristics of the terrain considered (for a crater: depth, diameter, and inclination of the borders) and geological features of the lunar soil (presence of irregularities) which might affect the stability of a landing vehicle.
- **Elevation of the Sun** – Level of solar illumination at the specific site; linked with the topography, and can affect the amount of ice present in the crater.
- **Radiations** – Level of radiations and particles at the specific landing site (related to the life support of the astronauts).
- **Accessibility** – Level of accessibility of the landing site and landing difficulty estimate. How easy it is to reach the landing site.
- **Probability of meteoroid impacts** – Probability of collision at the specific site.

However, the level of priority of each criterion changes with respect to the identified goals corresponding to the scenario. For each criterion previously described, a long-term view statement is provided in Table 2. Consequently, Table 3 summarizes the priority evolution of these parameters.

3.2. Lunar topography analysis tool

With reference to the criteria related to the topography of the surface discussed in Table 2, a preliminary analysis is presented in this section, in an attempt to foresee the areas likely to host the future lunar spaceport. The results here shown are meant to be an example of the strategy that could be implemented and are not meant to be exhaustive, as many more criteria could be put in place.

Due to its current scientific and economic interest, and the availability of data, the lunar south pole area is chosen. Publicly available data measured by lunar surface observation missions are retrieved and manipulated, to be easily shown and overlapped. A “good” landing site is here considered as an area that has a slope lower than 5° . Due to the morphology of the terrain, a second requirement had to be added to avoid landing within PSRs. In fact, these regions meet the slope requirement but have a hostile thermal environment which would result in technical difficulties and a prohibitive cost of operations of such a system [20]. Original data on these two criteria have been made available on the NASA MoonTrek platform, developed by the Jet

Propulsion Laboratory (JPL) [21]. They are directly derived from the Digital Elevation Model (DEM) of the Lunar Orbiter Laser Altimeter (LOLA) instrument on Lunar Reconnaissance Orbiter (LRO).

The retrieved data cover different area sizes and have different on-ground resolutions. Hence, it is necessary to manipulate the maps to cover the same area at the same resolution. This resulted in the coverage of a 152×152 km projected area with the South Pole in the center, with a 240 m px^{-1} resolution. The total surface considered is then $23 \times 10^3 \text{ km}^2$.

Intermediate results are reported in Fig. 1: Fig. 1(a) shows a shaded representation of the terrain of the area, derived from elevation data. Fig. 1(b) overlaps the areas with the unfavorable slope (higher than 5°), while Fig. 1(c) overlaps the known PSRs to the terrain map. The PSRs total area is $4.1 \times 10^3 \text{ km}^2$, which represents the 17.9% of the total area considered. The two constraint maps are merged, hence deriving the areas with a favorable slope that are not inside PSR, presented in Fig. 2. Note that all maps are projections of a portion of the lunar spherical surface, with an average radius of 1737.4 km.

The lunar South Pole is significantly more mountainous than other areas on the Moon, and several steep crater ridges are present. The available area ($3.5 \times 10^3 \text{ km}^2$), shown in blue in Fig. 2, is rather scarce and/or scattered close to craters, accounting for 15.1% of the total area considered. A surface transport system could be put in place so that settlements could still take advantage of ridges (for illumination conditions, for example). Such a system will likely need continuous paths with low slopes, hence this could be another use of these maps.

By way of example, a detailed map is presented in Fig. 3, centered on the proposed construction site for the Moon Village Association base [22] (indicated by a green dot). The largest areas with favorable conditions are highlighted with blue circles, which could represent a spaceport building site for the base (and potentially other south pole settlements). Red circles show close-by PSRs. Black and gray circles are added to provide a scale of distances from the station’s proposed site.

4. Overview of a potential spaceport site

Every spaceport site on the Moon will need to provide a set of services in order to fulfill its purpose and support the landing and takeoff of lunar vehicles. The first spaceport sites will only perform essential functions which will be determined by onboard technologies and their related requirements. As the lunar ecosystem grows, spaceports will become increasingly versatile and turn into fully developed ground stations. In this section, a review of the services to be provided by a potential spaceport site is presented. These services are divided into three groups: services provided to the spacecraft, services provided to the crew, and services provided to the landing site infrastructure itself.

Table 2
Time dependency of landing site selection criteria.

Resources	Resources are of extreme importance for long-term independent bases on the Moon. However, astronauts will be fully dependent on Earth and cargo supplies for the first few years or decades to come. This will nevertheless become inaccurate over time once habitats, assemblies, and robotic supports are well settled, and experiments demonstrated. In particular, it may be expected to see lunar subsurface volatile-oriented scientific missions, that would, for the establishment of lunar settlements, need consideration of locally and seasonally-timed illumination conditions [16]. Therefore, the Resources criterion will see its priority rise.
Communications and Coverage	Communications will likely be of extremely high importance for the Artemis program set of missions. However, the design of lunar orbiters and relays is expected to take place in the coming years. This manufacturing will provide partial coverage of the lunar surface by 2060 — leading to a decreased importance of the communication coverage criterion over time.
Topography of the lunar surface	Topography is a key factor, if not <i>the</i> key factor, driving the landings up to now, such as safe zones with a well-known harmless slope (i.e., a slope that is close to zero degrees). Technology, on the other hand, evolves in an exponential manner. It might thus be assumed that much more complex systems may enable landings in currently inaccessible areas. Such areas could be sloped terrain regions, as well as craters and their borders.
Elevation of the Sun	Today’s need for constant energy to communicate with Earth and the space stations (ISS, Lunar Gateway) is defined by the need of having constant illumination from the Sun. However, this might become less important once lunar habitats are expanded, as well as when batteries, fuel cells, and other life support systems become more efficient for life sustainability without constant sunlight.
Radiations	Radiations are widely taken into consideration as of today. Indeed, astronauts shall not encounter a certain dose of radiation so as to limit the risk of cancer or other life-threatening diseases, also due to the protection limitations of current structures. However, it is expected that the Artemis program will provide the science community with better insights into future robust, and efficient systems enabling reliable and mission-long protection against radiation fluxes.
Accessibility	In the 2020s, the cost of a launch and the minimization of fuel are what worries the stakeholders when willing to send something into outer space. Therefore, it might happen that, for the first couple of decades the same route(s) are used for any mission, no matter the nation. On the other hand, the more launches occur the more new routes will be necessary. For this reason, it might be wise to think of a decreased priority of the space trajectory and accessibility. Note that should the cost of a launch decrease drastically by 2054, the former is even more true. Considering the disruptive rocket technologies, and the emerging small launch vehicles due to lowered standard prices thanks to launchers’ reusability [17,18], it would not be surprising to have new regulations, along with additional launch complexes and routes, forthcoming during the 2020s and 2030s. Nevertheless, although the global number of yearly launches is undoubtedly going to rise – given the new capabilities of developing countries, including China [19], India, and Brazil – it is expected to observe a gradual improvement in space traffic management and policy agreed by all parties.
Probability of meteoroid impacts	The priority of this parameter may highly depend on the fidelity of the models — which could evolve throughout the missions and help mitigate the collision risk.

Table 3
Criteria priority evolution.

Criteria	2024	≤ 2054	> 2054
Resources	Medium	High	Very high
Communications	Very high	Very high	Very low
Topography	Very high	Very high	High
Solar Elevation	Very high	High	High
Radiations	High	Medium	Medium
Accessibility	Very high	Medium	Low
Meteoroid impacts	High	High	Very low

4.1. Services to the spacecraft

The first iteration of lunar spaceports will consist of little more than a platform on top of which lunar landers will be able to land. However, further evolution of landing sites could start implementing more advanced features. The capability to refuel a landed spacecraft is one of the most crucial functions a spaceport will perform. Refueling straight at the landing site means that spacecraft do not have to carry the fuel for the trip back to lunar or Earth orbit, which means smaller, simpler, and cheaper spacecraft that will translate into a reduction in costs. Implementing refueling capabilities means that the potential spaceport should be able to store fuel, and transfer it from the production source to the storage, and from the storage to the vehicle. Being able to safely purge fuel from the spacecraft is also necessary to correctly regulate tank pressure.

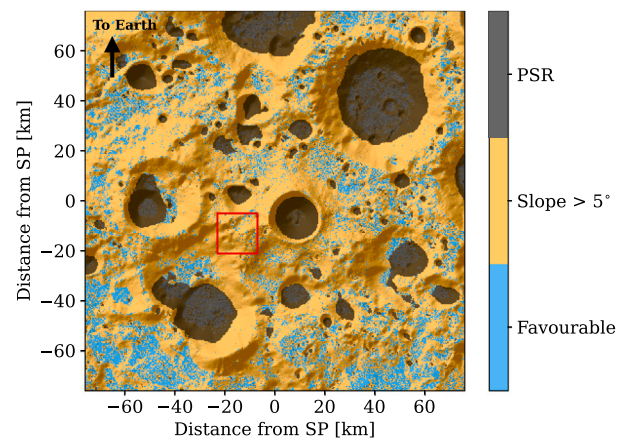


Fig. 2. Combined maps of Fig. 1. Red square identifies detailed map of Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Following refueling, having a power station at the spaceport will become a necessity in order to power the systems of the landing site, as well as to recharge spacecraft batteries in case of unexpected discharge. Moreover, providing a direct communications link with an Earth-based ground station will increase the data throughput for

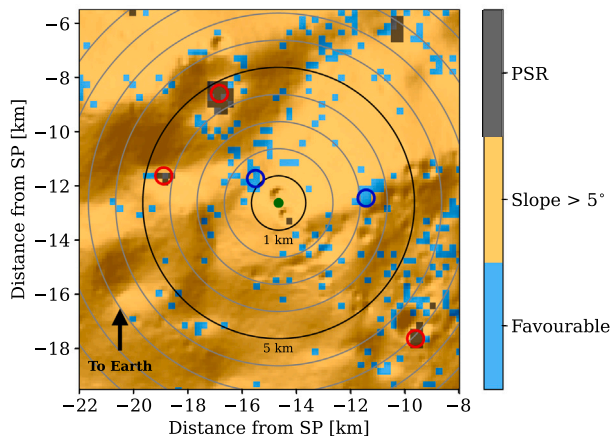


Fig. 3. Detail on a 14×14 km grid, centered around the proposed target (green dot) of the Moon Village association [22]. Details provided in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

science and commercial missions near the spaceport, allowing these missions to communicate with Earth much faster than by using their onboard antennas. Of course, having this functionality will be preceded by having a local communications system within the spaceport and its surroundings. This service will result useful not only for spacecraft but also for hypothetical Moon bases close to the spaceport.

Finally, advanced sites that are chronologically further in the future will provide repair and disposal services. This will ensure that the necessary infrastructure is available for astronauts or automated robots to perform repairs to the landed vehicle as well as to the landing port. Repairing vehicles on-site also means that there has to be a system in place by which faulty parts that are replaced or parts that have reached their End Of Life (EOL) can be disposed of in a sustainable manner. There might be the case that a landing vehicle as a whole reaches EOL at the spaceport, which forces the site to have a system to transfer a vehicle from the pad to a vehicle disposal site. Because performing maintenance operations on the landing pad itself would alter the normal flow of landings and liftoffs, having a separate maintenance site is also necessary, and the same system to transport vehicles can be used. Finally, storage of electromechanical equipment, tools, structures, and consumables must be present in order to ensure maintenance operations.

4.2. Services to crew

At first, the crew will be fully composed of astronauts that go to the Moon for scientific purposes and to increase the human presence in Lunar settlements. Mainstream space tourism is still far away, but as spaceflight prices go down and autonomy and safety of lunar spacecraft increases, flights to the Moon with crews that include paying customers will start to become commonplace. This way, lunar spaceports of the far future will need to address the necessities of both astronauts and tourists.

There is some functionality that will be common for both astronauts and tourists. There needs to be a way to extract crew from within the landing vehicle and to the surface or space designated for them, as well as to return from said space to the vehicle in case of departure. If the hatch for the crew is located in the upper part of the vehicle, as with the Starship Human Landing System, this means that some sort of elevator must be present if not already implemented in the spacecraft.

In situations where an emergency occurs or the spacecraft is simply not ready yet to lift off, a pressurized area for humans to wait or stay

sheltered is necessary. If astronauts or tourists have left their base (or the base is unavailable) and, for any reason, the vehicle cannot leave the Moon, the humans need to safely be able to wait for the problem to be resolved. This pressurized area together with its airlock can also be used in the case the landing vehicle does not have an airlock itself. In the short term, this area should have access to at least water and ideally also food in order to ensure that humans can survive the minimum time required for a rescue vehicle to arrive. An air recycling system or air tanks would also be desirable to ensure that astronauts can breathe.

In the situation where the transport of humans from the landing site to the base is done via a surface vehicle, the site should provide a recharging station for said vehicle. A crew module to enter and leave the vehicle must also be in place, along with an airlock that equalizes pressure in both habitable volumes, the one in the crew module and the one inside the surface vehicle. In further advanced landing sites, a facility to perform checks on the vehicle could improve its reliability and lifetime, especially if the facility also has the required infrastructure to perform small fixes and repairs.

Finally, in the far future, a welcome station for tourists where they can be medically checked and attended should be implemented on the site, in order to ensure that they are fit for flight before leaving Moon orbit, or that any damage that they might have suffered during landing can be taken care of.

All of these services are supported by storage space. As mentioned earlier, food and water must be stored along with air reserves. Storage for surface suits, tools, and machines as well as electromechanical equipment is necessary for all of the functions above to be performed.

4.3. Infrastructure

The infrastructure of a landing site embeds all the aforementioned functionality, as well as its maintenance. The infrastructure of a Lunar Landing Site that is intended for repeated use will need to be maintained if the operations on the Moon are to be sustainable. This means that obsolescence should be minimized by maximizing the lifetime and reparability of all the systems that compose the site.

One of the highest-priority elements to be developed is the site's landing pad [23]. Even the least advanced landing site that is used for sporadic vehicle operations will have a landing pad. Depending on the material of the pad, the stress caused by repeated landings and take-offs can induce erosion and degradation of the platform itself. In order to maintain this pad sufficiently horizontal for the vehicles to be able to stand, the pad should be refillable with additional material to replenish the material that is eroded.

A similar thing occurs with the launch (and landing) structure. A more advanced site that has a launch structure for larger vehicles, like launch systems on Earth, will need revision and maintenance. Air deposits, such as pressurized air tanks, are necessary for advanced sites. The tanks can be used for all the functionality mentioned in previous paragraphs as well as to refill the atmosphere of crewed vehicles. In further advanced landing sites, the air tanks could be replenished on-site, creating oxygen directly from lunar regolith [24].

In the same way, the infrastructure to store water at adequate temperatures is necessary. In advanced landing sites that have the capability to host humans for a relatively long amount of time, waste disposal or processing system should be in place. Because advanced sites will also provide the capability of performing repairs, a way to get rid of faulty material is needed.

As mentioned above, the landing site should provide a power post to recharge vehicles and also to power every system on the site. If the energy for the power post is produced at the site itself, be it via a solar panel farm, nuclear generators, or any other suitable form of energy generation, a way to store the energy and distribute it is necessary. If the energy is produced off-site, energy distribution within the landing site is still required, but storage can be moved to the generation plant

Table 4
Landing site evolution with time scale, divided in services for a Space Craft (S/C), crew or infrastructure.

	Service	Timeframe		
		Short-term	Mid-term	Long-term
Services to S/C	Landing pad	✓	✓	✓
	Power transmission from site to S/C	✗	✓	✓
	Communications link to Earth	✗	✓	✓
	Communications link to Moon base	✗	✓	✓
	Refueling post	✗	✗	✓
	Repair and disposal	✗	✗	✓
Services to crew	Extraction and insertion to/from S/C	✓	✓	✓
	Airlock	✓	✓	✓
	Pressurized emergency area	✓	✓	✓
	Surface vehicle station and airlock	✗	✓	✓
	Surface vehicle repair station	✗	✗	✓
	Tourist station (storage, health office)	✗	✗	✓
Infrastructure	Launch structure maintenance	✓	✓	✓
	Landing pad maintenance	✓	✓	✓
	Air storage	✓	✓	✓
	Water storage	✓	✓	✓
	Food storage	✓	✓	✓
	Waste disposal	✗	✓	✓
	Energy production and storage	✗	✓	✓
	Communications	✗	✓	✓
	GNC support	✗	✓	✓
	Housing for workers/tourist	✗	✗	✓
Management of vehicles and equipment	✗	✗	✓	

itself. Because a power outage can occur when the crew is on the site, a local backup generator is also needed.

Finally, a landing site could act as a relay station for communications. In a site where there are multiple lunar bases, a single landing site could act as a relay and router for communications among the bases, from bases to an orbital station, vehicles, or even communication with the ground station on Earth. This way, the more complex long-range communication system could be hosted in a single spot, instead of having multiple distributed on multiple bases. An additional advantage of this is that the landing site could act as Guidance Navigation and Control (GNC) support for the vehicles, acting as a radar on the surface, or as a navigation system in combination with other landing sites and spacecraft in lunar orbit.

All of the functionality here described is dependent on the time frame being discussed, with more and more functionalities being available in the long term. Table 4 summarizes the evolution of available services in time.

5. Landing site regulation

In the previous sections, a view has been provided on what lunar exploration might look like based on the current trends and interest to not only explore and understand the universe around us but also to exploit it. This behavior has always been part of human nature and there are many examples in human history, but not very often with a peaceful approach. Humanity will most likely be back on the Moon building settlements, pushing limits to develop new technologies and strategies that would allow living in such an extreme environment, while at the same time fostering international collaborations and partnerships.

Space Agencies and companies around the globe are working at a fast pace to achieve these objectives, and multiple robotics missions to the orbit and surface of the Moon are currently planned. A collaboration

between NASA, ESA, the Japan Aerospace eXploration Agency (JAXA), and the Canadian Space Agency (CSA) will bring during the 2020s the first space station in lunar orbit, also known as the Lunar Gateway [25]. It will serve as a staging point for robotic and crewed missions not only toward Earth’s only natural satellite but beyond Earth’s orbit, too.

However, the technical aspects and challenges of colonizing the Moon are not the only main topics discussed by space-related entities. There is also another aspect that is gaining particular attention: how to regulate activities on and around the Moon (and beyond). There are several international committees and working groups that are actively promoting discussions, such as the Committee on the Peaceful Uses of Outer Space (COPUOS), a United Nations Committee, or the Effective and Adaptive Governance for a Lunar Ecosystem (EAGLE), an action team of the SGAC, just to mention a couple.

The main challenge comes from the fact that the Moon and all the other celestial bodies have been declared unclaimed territories with the Outer Space Treaty, and should not be claimed by any entity (either state, organization, company, or private person) [26]. Nevertheless, the exploitation of the Moon from different points of view (for science, for resources, or for commercial purposes like tourism) is one of the main objectives. However, the question is if it can be done in a peaceful and sustainable way without laws and regulations, without having conflicts between different entities having the same interest. At this point, it seems improbable that this scenario could become a reality, especially in the long term when the number of actors that will join the new era of space exploration will increase. It is therefore evident that international agreements and cooperation represent the minimum that must be met.

This work addresses one particular aspect of the legal and regulatory framework that needs to be established for safe and sustainable activities on the Moon: Space Traffic Management (STM).

STM recently became a very critical topic due to the continuously increasing number of space participants (military, civil, and private)

and satellites launched in orbit, consequently inducing an increase of risks and dangerous consequences, both from an economic and political point of view. This sudden interest in space activities unveiled the inherent gaps of the system, guided only by non-binding international treaties, general principles, and national laws with an overall framework that is loose and ambiguous. In the last years, multiple articles, reports, and studies have been published proposing potential solutions:

- the foundation of an international organization that could coordinate the international effort, foster cooperation, invite experts in the field to define standardization of processes and requirements, and provide guidelines to national authorities but also to commercial entities, similar to what the International Civil Aviation Organisation (ICAO) did for civil aviation [27];
- national governments to ensure standardization of requirements, to streamline review and approval process (e.g., licensing) for public and private entities, to encourage sustainable concepts and technologies [28];

While there is still no definite implementation at an international level, some countries are taking the initiative at a national level, like the United States Space Policy Directive 3 which is going to shift the responsibility of Space Situational Awareness (SSA) from the Department of Defense to the Department of Commerce [29], and the European Union-funded SPACEWAYS project that aims to assess the European capabilities and needs for SSA and STM from a technical and regulatory point of view [30].

6. Conclusions and perspectives

This research is part of a multidisciplinary project initiated by the SGAC team TURTLE. The aim of the project is to evaluate risks and discuss potential solutions to the technological challenges for the fair and sustainable development of human settlements on the Moon. The landing site is one of the five topics covered in the project: the authors of the present paper invite readers to look for the presentations from the other teams in the International Astronautical Congress (IAC) 2021 Technical Program.

The choice of a landing site represents a crucial part of lunar surface missions. Especially in a future scenario, where multiple actors will need to access different parts of the Moon with a diverse range of spacecraft, the location of a “spaceport” will need to answer to multiple and conflicting requirements. This work reflects the idea of coordinated and peaceful access to the lunar surface, implying that a single spaceport will serve as an access point and hub for multiple missions. Hence, the focus has been on finding the metrics and factors that will influence the placement and design of such a central logistical asset.

In Section 3, key factors that make surface locations suitable for the construction of a spaceport are identified. Through the analysis of Lunar topological data, processed from publicly available sources, it was possible to scan the surface of the Moon, highlighting its characteristics. The example provided shows that by combining the discussed key factors, an estimation of the available area was obtained in the Southern region of the Moon, one of the most targeted areas by future missions. The same approach could be extended to include additional factors to refine the area estimation, considering for example the availability of resources or the soil density and roughness. The algorithm represents the first example of landing site selection workflow for spaceports, therefore is not related to specific research or scientific objectives. A limiting factor in the current version remains the availability and variety of satellite observation data. In the coming years of renewed exploration, it is likely that future missions on the Moon will contribute to the search for suitable locations that could host spaceports and the infrastructure for multiple commercial and research bases and settlements.

As described in Section 4, this paper also evaluates features and services for a landing site to become an efficient spaceport and support exploration or exploitation missions. The Moon is known to be an extreme environment. The development of self-sustaining and sustainable settlements will require substantial efforts and investments to develop the required technologies. A potential roadmap has been presented with the different services required by the “customers”, either vehicles or humans.

Lastly, in Section 5 the current challenges, discussions, and trends in the Space field from a legal perspective are briefly discussed. On one side, all the main stakeholders (space agencies, governments, or companies) are not willing to renounce the freedom of exploring and using space as done until today. On the other side, there is a general awareness that, in the long term, it might not be sustainable. The proposed idea is intended to support, promote, and increase awareness around the topic of what, and how, the authors believe should be regulated for a safe, sustainable exploration and exploitation of the Moon. The two examples presented for civil aviation and Antarctica should be considered in the international discussion since they represent evident cases of successful cooperation. It is unmistakably clear that the key to success is international collaboration and coordination.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank their friends and colleagues from the TURTLE focus group, for their support and continuous feedback on this work. Special thanks to John C. Mankins, for his insights into the Moon Village Association’s plans for future lunar settlements.

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