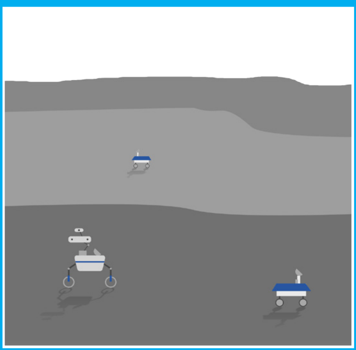
3.1 Phase 1: Robotic Surveillance

PHASE 1

ROBOTIC SURVEILLANCE

PRESENT	5 YEARS	2025
The first robotic missions are sent to the Moon.	Uncrewed spacecraft investigate the Moon and acquire data.	Settlement location will be selected. Preliminary quantification and classification of resources complere.



PURPOSE: To better **understand** the lunar **environment** in preparation for long-duration missions.

- In-orbit Moon **observation/remote sensing**.
- Surface **exploration** via controlled soft-landing, impactors, and rovers.
- **Identification** of potential habitat **sites**.
- Establish a **zone of safety** around lunar activity so as not to affect other activities.

OPERATIONAL DETAILS

The Robotic Surveillance phase acts as a precursor to all future exploration missions and settlement attempts on the Moon. Its fundamental purpose is to prospect lunar resources and identify potential outpost sites for long term habitats to develop. More specifically, data associated with lunar topography, surface environment, geodetic control, quantity of useful volatiles, and previously unknown characteristics will be collected. Acquiring this vital knowledge ensures more productive and safer human missions during later phases (NASA, 2013). Data will be obtained by surveying the lunar landscape via remote sensing techniques and characterizing the surface with probes and rovers.

The majority of roadmaps mentioned in the previous section allude to early precursor missions to polar sites to confirm the presence of water. This phase is technically already underway. This is shown by the completion of the Chandrayaan-1 mission focusing on lunar surface characterization from the Indian Space Agency, and the ongoing Chang'e missions from the Chinese Space Agency (CNSA), which address exploration of the far side of the Moon and future sample return missions. Other anticipated missions and their specific focus will be discussed later in Section 3.1.1.6. For Phase 1 to be considered a success, initial identification of in situ resources, along with their location and estimated quantity must be established in order to identify potential habitat sites. Furthermore, consideration of scientific potential and operational conditions heavily influences the selection of lunar sites.

The remaining sections within this phase present the operational requirements that are essential for the prospecting stage to be successful and more specifically, what aspects need to be addressed in terms of infrastructure and governance. It is noted here that the majority of the operational requirements of this phase are specific to each mission and method of lunar data extraction. An overview of these operational requirements is provided in Table 3.3, below.

Table 3.3. Overview of operational requirements for Phase 1

PHASE 1	
INFRASTRUCTURE	GOVERNANCE ASPECTS
Architecture • Identification of potential habitat sites with consideration of local terrain, energy availability, and communication aspects. Power and Distribution • Use of photovoltaic (PV) solar array based on mission requirements. • Potential use of RTGs, if proper waste disposal is present. Communication/Navigation • Direct communication link from orbiter/rover to earth ground station. • Potential need to implement relay satellite for communication access in remote regions (far side of Moon, craters, etc.). • Implementing ground based Lunar navigation for on surface missions. Transportation • Implementing the Commercial Lunar Payload Services (CLPS) program to deliver prospecting missions. In Situ Resources • Characterization of lunar regolith, polar volatiles, and lunar substructure via mass spectrometers and hyperspectral imaging.	• Global governance and international partnerships required for coordinating Lunar exploration activities. • Establishment of safety zones/operational boundaries for each party required to ensure individual missions success.

3.1.1 Phase 1 Infrastructure

The specific technology demonstration missions dictate the infrastructure requirements of the Robotic Surveillance phase are dictated by the specific technology demonstration missions. The necessary aspects for to the investigation of the Moon will be presented here.

3.1.1.1 Architecture

There is no architecture specifically being established on the Moon during this phase. The uncrewed spacecrafts will carry out investigatory missions of the lunar surface, acquiring data with regarding the abundance of resources, identification of potential habitat sites, and understanding of the lunar environment.

There are a number of potential locations on the Moon that have been proposed as possible strategic locations for a permanent lunar settlement. The site selection for human-based missions is mostly dictated by available resources, scientific potential, and operational considerations (NASA, 2013). More specifically, sites with many geological features support science-based missions, while sites containing or near to high-grade ore and metals are favorable for future lunar base development. Table 3.4 below presents the current high priority sites based on past lunar surveillance missions with their respective locations and critical features.

Table 3.4. Current high priority Lunar outpost sites (NASA, 2013)

Lunar Site	Location	Key Features
South Pole (rim of Shackleton)	**Polar** Latitude: 89.9° S Longitude: 180° W	• Near-permanent sunlight for power production • Oldest Lunar impact feature for science missions • Cold trap present (may contain water ice)
North Pole (rim of Peary B)	**Polar** Latitude: 89.5° N Longitude: 91° E	• Near-permanent sunlight for power production • Cold trap present (may contain water ice)
Rima Bode	**Equatorial** Latitude: 13° N Longitude: 3.9° W	• Extensive high-Ti mantle deposits (useful for ISRU) • Exotic Xenolith ash deposits for science missions • Based in equatorial region (easy access)
Aristarchus Plateau	**Mid-Latitude** Latitude: 26° N Longitude: 49° W	• Diverse geological area for science missions • Contains pyroclastic deposits (useful for ISRU)
Orientale Basin Floor	**Mid-Latitude** Latitude: 19° S Longitude: 88° W	• Unique crater morphology for science missions • Contains mare & highland regolith (useful for ISRU)
Central Far Side Highlands	**Mid-Latitude** Latitude: 26° S Longitude: 178° E	• Primordial crust for science missions • Al- and Ca-rich regolith (useful for ISRU) • Low-frequency radio sky for astronomy missions

During this phase it will be essential to determine, through ground truthing of preliminary lunar observation studies, what resources are available, where they are most abundant and what quantity of those resources is present. All of this must be considered, while keeping in mind the temperature and radiation exposure characteristics of each potential location, as well. In order to make the most informed decision as to the established location of a permanent human settlement, a variety of aspects must be taken into account. These include:

- **Terrain**: selection of the site to minimize safety risks during landing. Also, analyze the terrain to assess for the presence of useful resources.
- **Energy**: selection of conditions to ensure energy production, storage, and distribution for robotic operations and bases should be located close to areas with long periods of illumination for efficient use of solar energy (Eckart, 2006).
- **Thermal constraints**: temperature variation depends on location (-173°C to 127 °C). The ideal solution to limiting thermal constraints is to find a location with lower temperature variations, which would reduce structural stresses, electrical and thermal control system damages.
- **Communication**: the chosen site should ensure a stable communication link with the Earth. It might be necessary to establish satellite communication via Earth-Moon Lagrange points (for coverage on polar regions).
- **Navigation**: The need for a ground-based lunar navigation system during exploration of craters.
- **Dust contamination**: dust mitigation technologies are a key enabling factor for performing extended duration lunar surface missions. Infrastructure preparation will potentially raise a lot

of dust, which is harmful to robots, so that the mitigation will be crucial for this stage (ISECG, 2018).

3.1.1.2 Power and Distribution

Only limited power is needed in Phase 1, since low power demand surveillance activities will predominante. It is essential that the power and distribution solution that is used is sustainable, since current international treaties require avoiding polluting the Moon (UNOOSA, 2017). To make sure they are sustainable, advanced management, control, and disposal functions are essential. The rovers that will explore selected areas, to identify the best habitable locations, should be part of a remote coordinated surveillance effort and should have a self-sufficient, mission specific, power supply, and control system.

The abundance of sunlight on the Moon, approximately 1.5 times the amount as on Earth due to the absence of atmospheric influences (e.g., clouds, wind, and rain), make electromagnetic radiation from the sun an ideal in situ, renewable, and clean source of energy (Kumar, 2006). More specifically, the light of the sun is converted through photovoltaic arrays into electrical power which makes it a simple solution with only limited points of failure. The potential power sources could be a combination of a PV array and batteries for storage as part of the rover design. Alternatively, radioisotope heater units (RHU) or radioisotope thermoelectric generator (RTG) could be implemented, which have flight heritage and little sensitivity to temperature gradients and radiation (O'Brien, et al., 2008). However, due to the radioactive decay process, methods of radioactive disposal must be addressed to ensure the sustainable exploration of the Moon while generating zero waste. As will be described in the following Section 4 on Lunar Sustainability Goals, this would maintain compliance with the Lunar Sustainability Goals "Sustainable ISRU" and "Zero Waste."

3.1.1.3 Communication

The Earth-Moon communication that will take place during this phase is highly mission-specific to the individual robotic missions that would be taking place. Some missions may not need developed communications architecture, as they would use direct communication with ground stations on Earth using radio frequencies which were also used for the Apollo missions (Dietz, et al., 1972). Any robotic mission that will be conducted past the horizon, down in a crater, or anywhere else out of the line of sight from its lander (or orbiter), will require an orbital relay satellite, such as the one shown in Figure 3.2 which was used for the Chang'e-4 mission.

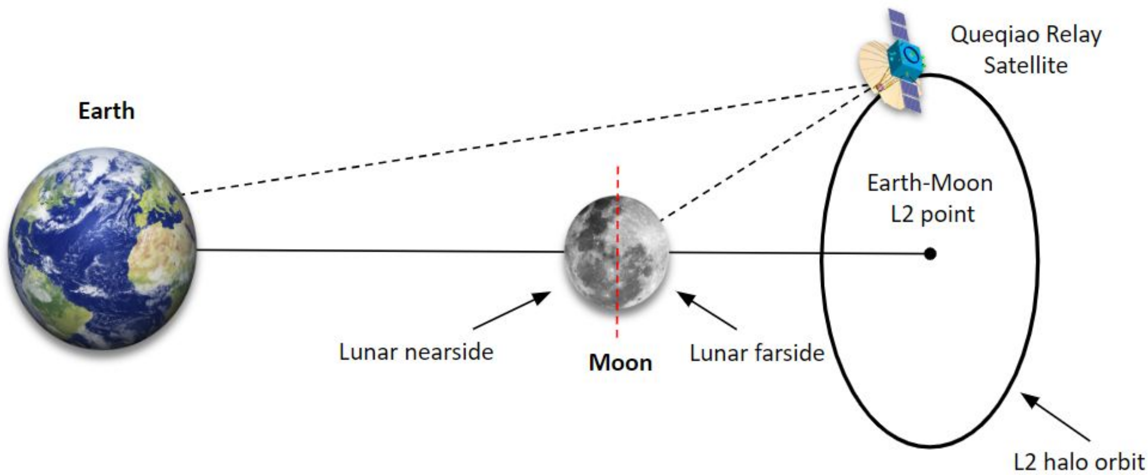


Figure 3.2. Queqiao relay satellite for Chang'e-4 in L2 halo orbit (Xu, 2018)

3.1.1.4 Navigation

Phase 1 requires rovers exploring the surface and operating in areas far from the landing site. For this purpose, a ground-based lunar navigation system would be appropriate. A ground-based lunar navigation system typically relies on the implementation of machine-vision-based-autonomous navigation, by post-processing stereo images taken from the viewpoint of a rover. Adjacent images are cross-correlated to assess local location and orientation of the rover and, in principle, the results obtained could be matched to satellite generated ground images (Li and Zhong, 2016).

Alternative methods of surface navigation include the use of consecutively logged rover positions to produce displacement maps within a common coordinate system, ultimately being able to produce local elevation maps (Moesl, et al., 2005). Furthermore, it could be extended to other ground-based transportation systems in the next phases, although the low accuracy of such a ground-based lunar navigation system could lead to the development of a more complex and expensive, space-based lunar navigation system.

3.1.1.5 Transportation

With the use of robotic probes and rovers to prospect the surface, methods of transporting the scientific instruments from Earth for analysis are required. Current and future planned robotic missions to the Moon indicate the use of standard chemical propulsion systems. While using these type of rockets, it is estimated that one kilogram of mass will cost between $35,000 and 70,000 USD to be transported from Earth to the Lunar surface (Kutter and Sowers, 2016). To reduce these costs, programs such as the Commercial Lunar Payload Services (CLPS) have been established, which allow selected companies (e.g., Lockheed-Martin, Moon Express, Orbit Beyond) to deliver scientific payloads to the Moon at reduced cost (NASA Science, 2018). Given the nature of these prospecting missions, the need for transport back to Earth is not required. However, for surface-based surveillance missions via rovers, soft landings are required, which has only been achieved by the US, Russia, China, and soon Israel (Guo and Han, 2010). Transportation capabilities from the commercial space industry will transition towards a more reusable form, as will be discussed in the next phase, which is critical in order to support the goal of "Sustainable Transportation."

3.1.1.6 In Situ Resources

As mentioned previously, the fundamental purpose of this phase is to quantify the useful resources and asses potential habitat sites on the Moon. There are a variety of methods and scientific instruments to characterize the lunar surface. A table summarizing planned missions, instruments being implemented with their goals, and the resource being assessed is shown in Table 3.5, below.

One of the major resources of interest on the Moon is water ice. Past missions have identified its presence in the polar regions, deep within permanently shadowed craters, and even trapped within the lunar regolith itself (NSS, 2018). Water ice has a variety of possible uses for future human missions, the most critical of which is astronaut hydration and survival. Other aspects include applying electrolysis to obtain hydrogen and oxygen, which then can be used as a rocket propellant, which would greatly improve Earth-Moon transportation logistics. Furthermore, oxygen alone could be used in astronaut life support systems.

Aside from water ice, the basaltic lava regions of the Moon have compositions of metals (i.e., iron, titanium, aluminum, and more.) and silicon which would prove useful for habitat construction and mirror fabrication (Fischer, 2018). Although composition of lunar regolith changes based on location, Table 3.6 provides an indication of the breakdown with anticipated uses for each element.

Table 3.5. Summary of resource identification missions with corresponding instruments (ISECG, 2017; Zak, 2015; Wurz, et al., 2012; IKI RAZ, 2019; Hashimoto, et al., 2011)

Mission	Agency	Instrument and Goal	Resource Assessed
Luna Glob	ROSCOSMOS	• Active neutron and gamma-ray analysis for elemental composition of the surface structure • Laser mass-spectrometer for soil composition • Infrared spectrometry of minerals	• Lunar Soil • Lunar Regolith
Polar Sample Return	CNSA	• Subsurface drilling/acquisition • Analysis performed back on Earth	• Polar volatiles (H_2, O_2, ice water)
Luna 27	ROSCOSMOS	• Active neutron and gamma-ray analysis of surface (remote sensing) • Radiometer-Thermometer for temperature measurements of subsurface regolith (remote sensing)	• Lunar surface • Lunar regolith
Chandrayaan-1	ISRO	• Imaging spectrometer for spectral mapping of the lunar surface (remote sensing)	• Ice water • Iron-bearing minerals (pyroxene)
Resource Prospector	JAXA	• Broadband (VBB) and short period seismometers • Spectro-microscope imaging for mineral identification • Active X-ray spectrometer for chemical analysis of soil	• Lunar substructure • Lunar regolith

Table 3.6. Useful elements available within lunar regolith with estimated quantity (Fischer, 2018)

Element	Usefulness/ Purpose	Average Composition (by weight)
Oxygen	• Required for life support system • Potential use as in situ rocket fuel	43%
Silicon	• Use for semiconductor manufacturing • Wafers of single-crystal silicon for solar cells	21%
Iron	• Strong material for construction	13%
Calcium	• Adds to structural integrity	8%
Aluminum	• Construction of mirrors for solar collection and reflective coatings for spacecraft	6%
Magnesium	• Provide stability to structures	5%
Chromium	• Important alloy for structural stiffness	2%
Titanium	• Important alloy for structural stiffness	2%

3.1.2 Phase 1 Governance Aspects

Several countries have outlined plans to send robotic explorers to the Moon, including: China, South Korea, Russia, India, Israel, Japan, US, and ESA, all with planned missions to explore the lunar surface with different objectives. In the initial phases, global governance will be essential to coordinate activities, and exists as an important component for achieving a sustainable use of the Moon and meeting the Lunar Sustainability Goals set out in Section 4 of this paper.

Governance in the first phase will mainly consist of international partnerships and agreements, as exists today with partnerships such as the ISS, and groups such as the International Space Exploration Working Group. These partnerships should be extended to the Moon and should expand to incorporate new members.

Guaranteeing open access to the Moon (Goal 1: Open Access) should form the basis of initial governance, from which other more complex governance could develop over time as the phases develop. Another critical requirement for Phase 1 activity will be to establish safety zones (operational boundaries) to ensure the safety and success of missions on the lunar surface.

A key benefit of a strong working system of governance would be to allow for the sharing of all crucial information with regards to ongoing and future lunar activities, including the mission objectives, the area of operation, mission duration, and more. Good governance could also help create an environment for collaboration (Goal 4: International Cooperation), particularly in the sharing of scientific data with regards to the lunar and cislunar environment, gleaned from robotic sampling activity.

3.1.3 Phase 1 Summary

The Robotic Surveillance phase has shown an underlying focus on assessing the usability of in situ resources on the Moon via in-orbit remote sensing and rovers. Due to the prospecting nature of this phase, habitat-based architecture is not present. However, a focus on outpost location identification, with consideration of the local terrain, energy availability, and communication aspects. Furthermore, the power requirements discussed are specific to each mission and the on-board instruments. The general use of solar arrays and potential implementation of RTGs, if proper disposal of waste is available, is the anticipated source of power.

Communications during this phase are based on line-of-sight to Earth ground stations. However, implementation of a relay satellite during exploration of remote regions of the Moon (e.g., beyond the horizon, far-side, and craters) may be required. Transportation for the mentioned robotic prospecting missions would be reliant on commercial launchers with specific involvement of the Commercial Lunar Payload Services.

Current and proposed missions have shown a focus on characterizing lunar regolith, polar volatiles (e.g., water ice), and assessing the subsurface lunar structure using a variety of scientific instruments. These current and proposed missions are being undertaken by a variety of nations. To ensure sustainable and progressive exploration of the Moon during this phase, international partnerships and a system of global governance must be in place.