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The Cold Harvest: Integrated Analysis of Volatile Sequestration and Landing Site Viability at the Lunar South Pole

Shreya Mane[1]

[1]Department of Research and Development, ASTROEX RESEARCH ASSOCIATION, Deoria-274001, India

ABSTRACT

The existence of Permanently Shadowed Regions (PSRs) and their distinct thermal environment have made the Lunar South Pole the main focus of international space exploration. Significant deposits of water ice and other volatiles necessary for In-Situ Resource Utilization (ISRU) are thought to be present in these "cold traps". In order to assess the geological makeup of the South Pole-Aitken (SPA) Basin and propose high-priority landing locations, this article synthesizes recent data from the Artemis program, China's Chang'e missions, and India's Chandrayaan series. We conclude that, despite the tremendous potential for resources, the main obstacles to sustainable living remain topographical difficulties and cryogenic engineering limitations. Because it has topographic high points with >50% solar illumination, the lunar south pole is being explored. Permanently shadowed regions (PSRs), which may store resources in the form of volatile compounds, are another reason why the south pole is being sought. Geologically, the pole is situated on the rim of Shackleton Crater, which has a diameter of about 21 km. This crater is situated on the topographic rim of the South Pole-Aitken (SPA) basin, which has a diameter of about 2,500 km and is the largest and oldest basin on the Moon.

Keywords: Scientific Goals and Motivation, Geographical and Physical Characteristics of the Lunar South Pole, Strategic Landing Site Evaluation, Challenges to Exploration

INTRODUCTION

For several reasons, including the operationally appealing potential of permanently shadowed areas with water ice [1] and permanently sunlit areas [2], as well as the scientific potential of a polar site for lunar-based astronomy [3] and general geological exploration of the Moon [4], the Polar region of the Moon has drawn attention as a potential exploration target. The Lunar South Pole is a terrain of stark contrasts, in contrast to the equatorial areas seen during the Apollo era. Deep crater floors are seldom exposed to sunlight because of the Moon's small axial tilt (1.5 degree C), whereas elevated rims are almost always illuminated.

Space mission planners and designers have several reasons to think about the lunar south pole when deciding where to deploy both human and unmanned spacecraft (e.g., robotic landers and rovers, short-term and long-term manned bases). Favourable thermal and solar energy conditions at particular brightly lit sites are a key justification for deployment near the lunar south pole, aside from scientific research and predicted in situ material resources. The majority of spacecraft sent to lunar locations need energy storage (either batteries or fuel cell devices) and solar power generation.

The majority of clear spots on the Moon's surface have roughly 15 days of light and 15 days of darkness. However, due to high, shadow-casting terrain at different distances from the deployment location, it is feasible to have more than 15 days of lighting with a divided illumination-darkness period close to the poles due to terrain heights and Sun elevation angles. Furthermore, even though a higher percentage of illumination is obviously advantageous, more illumination-darkness categories are even more beneficial because they lower the maximum shadow period, which lowers the deployed power system mass (particularly for energy storage). Consequently, extended illumination times and shorter, smaller, lighter, more mission-enhancing power systems are made possible during dark periods.

The largest and oldest well-preserved impact structure on the Moon is the approximately 2500-km-diameter South Pole–Aitken (SPA) basin [5-7]. It is also one of the few "massive impact structures" or post-accretion impact structures in the solar system with a diameter of more than 10,000 kilometers. As a result, the SPA's large impact is an important record of the dynamics of the early solar system and probably had a significant impact on the history of the moon [8]. Finding the SPA basin's radio isotopic age would help date other solar system entities [10] and serve as a crucial starting point for the history of lunar cratering [9]. Ages for the SPA basin that range from 4.26 to > 4.33 billion years ago (Ga) have been suggested by crater-counting chronology, Apollo sample, and meteorite investigations [11–16]. However, these estimates need to be verified by direct in situ sampling from the SPA basin.

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Scientific Goals and Motivation

Operational problems with solar power and unstable supplies that could support a sustainable exploration program are the main drivers of a South Pole landing. Additionally, access to the lunar surface will offer a chance to pursue scientific goals that are widely acknowledged as significant by the global community [17–20]. According to the National Research Council (NRC), there are concepts to be explored in future lunar missions. The lunar poles are unique settings that may have witnessed the volatile flux during the later portion of the solar system's history, according to idea 4. This idea anticipates studies that examine the source, modification, transport, retention, and composition of volatiles that might be present at the poles. The idea also discusses the investigation of cold regolith, whether volatiles are retained in the regolith, and the consequences for the prehistoric lunar environment. Because they can be processed into the resources required to construct a sustainable space exploration program (such as propellant, oxygen, and potable water), water ice deposits are particularly interesting for lunar ISRU endeavors [21–25].

Geographical and Physical Characteristics of the Lunar South Pole

Location and Coordinate System

Similar to the South Pole on Earth, the lunar South Pole is situated on the Moon at latitude 90° South. It is located close to the edge of multiple sizable impact craters and is part of the Moon's highland landscape. Because of the Moon's tiny axial tilt—roughly 1.54 degrees—the Sun stays quite near to the horizon at the poles during the lunar year, in contrast to Earth. Because of this, certain regions see constant or very constant sunlight, while others are always dark.

All meridians converge at the South Pole because the Moon's coordinate system arbitrarily defines longitude at the poles. Due to the diminished significance of traditional longitude-based navigation, this convergence presents special navigational issues for both robotic and human operations.

Topography and Major Craters

Rough terrain formed by meteorite impacts over billions of years dominates the lunar South Pole region. Highland plateaus, deep craters, ridges, and irregular regolith deposits make up the surface. The following are a few of the area's most notable craters:

- Nearly precisely at the South Pole, Shackleton Crater (≈21 km diameter) is one of the most researched craters. Its rim receives almost constant sunlight, which makes it a perfect place to generate solar energy.
- **Haworth Crater:** A deep crater with possible ice deposits and areas that are constantly shaded.
- **Shoemaker Crater:** Known for its intricate geological structure, it bears the name of planetary scientist Eugene Shoemaker.
- **Faustini Crater:** Because of its close vicinity to PSRs and comparatively solid topography, it is a potential landing site for future missions.

This area's extremely uneven topography, including steep slopes, jagged ridges, and boulder-covered surfaces, poses serious risks to both landers and rovers.

Permanently Shadowed Regions (PSRs)

The existence of Permanently Shadowed Regions (PSRs) is one of the lunar South Pole's most distinctive physical features. Sunlight strikes the poles at very low angles because of the Moon's small axial tilt. Because of this, deep crater floors are always black and never receive direct sunshine.
Important PSR Features:

- They are among the coldest places in the solar system, with temperatures as low as −160°C to −240°C.
- Preservation of volatile substances, such as ammonia, carbon dioxide, water ice, and methane.
- Because of their geological durability over billions of years, they can serve as organic cold traps for materials from the ancient solar system.

Because they may preserve early solar system chemistry and contain pristine records of cometary and meteoritic impacts, these areas are of great scientific interest.

Illumination Conditions and Peaks of Eternal Light

Some crater rims around the South Pole, known as "Peaks of Eternal Light," receive almost constant sunshine, in contrast to PSRs. These regions are perfect for the following because they receive sunlight for up to 80–90% of the lunar year:

- Generation of solar power
- Creating dwellings on the moon
- Extended scientific operations

Long shadows produced by the continuous low-angle sunlight make surface imaging and navigation more difficult, but they also aid in the identification of topographical features.

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Thermal Environment

One of the solar system's most extreme heat conditions can be found in the lunar South Pole. The distribution of temperatures is rather uneven:

- Temperatures in sunlit locations can range from +100°C to +130°C.
- Shadowed areas: May experience temperatures below -200°C.
- As an insulator, subsurface regolith keeps temperatures comparatively constant compared to the surface.
- For spacecraft, robotics, and human habitation, this severe temperature gradient poses significant engineering issues that require sophisticated thermal management systems.

Regolith and Surface Composition

Regolith, a coating of fine dust and broken rock created by frequent micrometeorite impacts, covers the lunar South Pole's surface. The characteristics of polar regolith are distinct:

- It is a great natural insulator due to its high porosity and low heat conductivity.
- Includes minerals such as magnesium, sulfur, iron oxide (FeO), titanium dioxide (TiO_2), silicon dioxide (SiO_2), and aluminum oxide (AlO_3).
- The regolith grains may contain trapped volatiles and hydrated minerals.

These minerals are essential for in-situ resource utilization (ISRU), which includes the extraction of metals, oxygen, and building supplies for lunar infrastructure.

Gravity and Geophysical Properties

At the South Pole, the Moon's gravity is about one-sixth that of Earth (≈1.62 m/s^2. Due to buried dense minerals and old impact basins, the area also displays gravitational anomalies and mascons (mass concentrations). Moonquakes are caused by thermal expansion of the crust, meteorite impacts, and Earth's tidal forces. To comprehend the internal structure of the Moon, polar seismic data is crucial.

Radiation and Space Environment

The Moon's absence of a strong magnetic field and atmosphere, in contrast to Earth, exposes the South Pole to solar wind particles, galactic cosmic rays, and extreme solar radiation. But occasionally, a portion of the polar region travels through Earth's magnetotail, changing the local plasma environment. Subsurface dwellings and regolith protection are essential for human survival in this hostile radiation environment.

Visibility and Communication Constraints

Direct line-of-sight contact with Earth is restricted because of the curvature of the Moon and the shape of the pole. Relay satellites in lunar orbit or surface-based communication towers positioned on elevated crater rims are frequently needed for missions.

Lunar Volatiles

Perhaps the most fascinating research we can do on the Moon with Artemis is produced by these strange habitats. Following Apollo, scientists thought that the lunar surface was dry and that stable volatiles, particularly H2O and OH, could not exist there due to the Moon's tremendous temperatures. Because of the chilly surface environment, particularly in locations that are permanently shaded, it was theorized that the poles would contain surface volatiles. We now know that volatiles gathered over the Moon's history are preserved in vast stretches of everlasting darkness in the polar regions. The distribution of volatiles in the lunar poles is complicated by recent remote sensing data; not all areas of permanent darkness contain volatiles, and some places are partially lighted but seem to maintain volatiles at or near the surface.

The constraints on volatile dispersion, transit, and retention will be limited by robotic and crew examination of these areas. By carefully collecting and returning these volatiles to Earth, we will be able to determine their age and place of origin, which will help us understand how water is distributed throughout the Solar System. There are conflicting theories regarding the origin of lunar water: some may have come from the lunar interior, reflecting water remnants from the Moon's formation more than 4.5 billion years ago; some may have come from comets and asteroids that have struck the Moon throughout its history; and some may be forming now due to solar wind interacting with the surface. In the end, each of these events may have contributed to what is seen at the surface today, but we won't be able to completely understand the lunar volatile history until we have samples in labs on Earth.

Location and Polar Geometry

The point where the Moon's axis of rotation crosses its surface is known as the lunar South Pole, and it is situated at latitude 90° South. The Moon's poles are located on solid, extensively cratered highland terrain, in contrast to Earth, where the poles are encircled by oceans and ice caps. Compared to Earth, which has an axial tilt of 23.5°, the Moon has an obliquity of only 1.54°. Throughout the lunar year, the Sun stays near the horizon at the poles due to this little tilt. As a result, illumination conditions are quite unusual, with some regions seeing nearly continual sunlight while others endure billions of years of darkness. All longitudes converge at the pole, making longitude ambiguous and making mapping and navigation more difficult. For surface operations, spacecraft use local reference frames and specialized coordinate systems. All longitudes converge at the pole, making longitude ambiguous and making mapping and navigation more difficult. For surface operations, spacecraft use local reference frames and specialized coordinate systems.

Topography and Surface Morphology

Over billions of years, meteorite strikes have significantly altered the old highland landscape that defines the lunar South Pole region. The surface morphology consists of:

- Different-sized impact craters
- Elevated peaks and rims of craters
- Depressions and deep basins
- Broken bedrock and boulder fields
- Deposits of fine-grained regolith

Significant Craters Close to the South Pole

The polar landscape is dominated by several big craters that are of great scientific and exploration interest:
Nearly exactly at the pole, Shackleton Crater (~21 km diameter) is thought to be a desirable location for future lunar outposts since its rim receives practically constant sunshine.

- Haworth Crater: This deep crater is thought to hold substantial ice deposits since its floors are continually shaded.
- Shoemaker Crater is a complicated impact site with geological strata and high slopes.
- Faustini Crater: A possible landing spot featuring areas that are both shaded and lit.
- NASA's LCROSS impact experiment, which verified the existence of water ice, was conducted at Cabeus Crater.
- Landing and rover traversal are difficult due to the highly rough terrain, which has slope angles of more than 30° in numerous places.

Strategic Landing Site Evaluation

The Lunar South Pole landing site selection is a challenging optimization problem. In contrast to the Apollo missions, which preferred level equatorial plains for safety, South Polar missions must strike a balance between three competing needs: direct line-of-sight to Earth for communication, maximum sunshine for electricity, and maximum shadow for ice access.

1. **The Shackleton Crater Rim**
   The "crown jewel" of lunar exploration is Shackleton. Its inside is always dark, but its rim is angled so that it receives approximately 80–90% continuous illumination.

   Strategic Advantage: The crater floor, which is only a few kilometers distant, probably has significant hydrogen concentrations, and the rim offers a steady solar power supply.

   The terrain is very steep, which presents an engineering challenge. To avoid falling into the 4.2 km deep crater, a craft must land with sub-meter precision on a tiny, high-altitude ridge.

2. **Malapert Massif (The "Malapert Mountain")**
   This vast highland region is one of the Moon's most strategically important landmasses, situated around 120 kilometers from the pole. Communication Hub: It has a nearly continual "view" of Earth due to its height. For the purpose of supporting operations farther into the shadows, this makes it the perfect site for a primary communication relay station.

   Thermal Stability: The "thermal shock" to lander electronics during the day-to-night transition is less severe here than it is on the crater floors.

3. **Connecting Ridge (Shackleton-Henson)**
   One of the best locations for the Artemis III human landing is the ridge that connects Shackleton to Henson Crater.
   Accessibility: In contrast to the rugged peaks of the Massifs, it provides a comparatively "flat" (slopes < 10°) landing zone.

   Science Potential: Astronauts can sample both more recent volcanic ejecta and ancient SPA basin material because it is situated on the boundary of multiple distinct geological units.

4. **de Gerlache Rim (Zones 1 and 2)**
   The de Gerlache crater's rims are special because they offer "seasonal" benefits.
   The "Double-Shadow" Advantage: Because some neighboring locations are under Earth's "radio shadow," terrestrial radio interference is prevented, making them ideal for upcoming Lunar Far-Side Radio Astronomy.

Resource Proximity: It is close to some of the biggest known "cold traps" on the pole, where ice is probably present right at the regolith's surface.

Site Name	Sun Exposure	Earth Comm.	Landing Difficulty	Primary Use Case
Shackleton Rim	High (90%)	Intermittent	Very High	Power Generation/Ice Mining
Malapert Massif	Moderate	Constant	Moderate	Communication Relay/ Base Camp
Connecting Ridge	High	Good	Low/Moderate	Human Landing (Artemis)
Leibnitz Beta	Moderate	Good	High	Deep Crustal Science

The process of finding areas of great scientific significance that provide secure and practical circumstances to support scientific improvements for upcoming exploration trips to the lunar south pole is known as landing site selection [26]. It is distinguished by a variety of geological formations and material resources dispersed throughout the area [27]. To properly investigate these varied areas, scientific missions like in-situ exploration and sample return programs need a coordinated strategy [28, 29]. Therefore, a key factor in choosing landing locations for particular missions must be the capacity for scientific discovery [30]. Water-ice is especially essential since it is a source of drinking water and can break down into hydrogen for fuel and oxygen for life support [31], which makes it an important consideration when choosing a location. However, severe sun conditions and difficult surface habitats are common in water-ice-rich locations [32], making direct landing attempts more difficult. Therefore, selecting safe landing locations close to priority water-ice reservoirs is a major difficulty in landing site selection research.

Challenges to Exploration
The technical obstacles have changed from theoretical to immediate operational issues in 2026 when China's Chang'e 7 aims to reach the south polar surface and the Artemis II mission gets ready for its crewed flight.

Four "Extreme Frontiers" can be used to group the main obstacles to Lunar South Pole exploration:

1. **The Lighting Paradox**
   The 1.5-degree C axial tilt of the Moon produces a lighting environment that is unmatched on Earth.

   Dangers of Navigation: Miles of shadows are cast by the sun's constant presence on the horizon. This causes "pitch-black" pits next to dazzlingly bright ridges, which confuses conventional cameras and prevents human eyes from perceiving depth.

   The Gap in Power: Although "Peaks of Eternal Light" provides solar electricity, a lander in a crater shadow ten meters away might be left in complete darkness. The current missions must land precisely (within 100 meters) to reach these small "solar islands."

2. **Cryogenic Engineering (The "Thermal Nightmare")**
   Some of the lowest temperatures ever recorded in the solar system can be found at the South Pole.

   Thermal Shock: Temperatures fluctuate from 130°C (266°F) in sunlight to -248°C (-414°F) in shadow.

   Hardware Survival: Common electronics and lubricants either grow brittle and break or freeze solid. To keep their circuit boards from breaking, rovers built after 2026 will need to store heat using Radioisotope Heater Units (RHUs) or sophisticated "phase-change" materials like octadecane.

3. **The "Glass Dust" Problem**
   At the poles, lunar regolith, or dust, is extremely hazardous.

   Abrasiveness: Polar dust is as sharp as tiny glass fragments because it is never "tumbled" by solar wind or heat in the shadows.

The dust has an electric charge, which causes static adhesion. It's "tumbled" itself to seals, space suits, and solar panels.

2026 Innovation: NASA is testing Electrodynamic Dust Shields (EDS), which are essentially transparent force fields that "flick" dust off solar cells and camera lenses using electric pulses.

4. **The Communication Blackout**
The Lunar South Pole is frequently hidden behind the Moon's "bulge" or obscured by enormous crater walls like Shackleton, which is deeper than the Grand Canyon.

Direct-to-Earth (DTE) Limits: Earth is only visible from the pole approximately 14 days a month, and even then, it is at a relatively low altitude.

The Relay Solution: "Lunar GPS" and relay constellations, such as NASA's LunaNet or ESA's Moonlight, which employ satellites in highly elliptical orbits to reflect signals from the deep shadows back to Earth, are now essential for dependable exploration.

CONCLUSION

The Lunar South Pole is now the cornerstone of the space economy of the twenty-first century, not just a place of interest. We must become proficient in cryogenic robotics and precise landing if we are to successfully "harvest" the pole. Although the water is present, the data from 2024 to 2026 indicate that it is probably more heterogeneous (patchy) than anticipated, necessitating mobile, "hopping" extraction units as opposed to stationary mines. A frontier in space exploration with enormous scientific, technological, and strategic importance is the lunar South Pole. It is a key component of future space exploration efforts due to its distinctive weather conditions, possible water ice supplies, and adaptability for extended human missions. In addition to advancing lunar science, ongoing investigation and study will open the door for human expansion throughout the solar system.

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