A Review of Lunar Communications and Antennas

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Over the previous two decades, a notable array of space exploration missions have been initiated with the primary aim of facilitating the return of both humans and robots from Earth to the moon. The significance of these endeavors cannot be emphasized enough as numerous entities, both public and private, from across the globe have invested substantial resources into this pursuit. Researchers have committed their efforts to addressing the challenges linked to lunar communication. Even with all of these efforts, only a few of the many suggested designs for communication and antennas on the moon have been evaluated and compared. These designs have also not been
shared with the scientific community. To bridge this gap in the existing body of knowledge, this paper conducts a thorough review of lunar surface communication and the diverse antenna designs employed in lunar communication systems. This paper provides a summary of the findings presented in lunar surface communication research while also outlining the assorted challenges that impact lunar communication. Apart from various antenna designs reported in this field, based on their intended usage, two additional classifications are introduced: (a) mission-based antennas—utilized in actual lunar missions—and (b) research-based antennas—employed solely for research purposes. Given the critical need to comprehend and predict lunar conditions and antenna behaviors within those conditions, this review holds immense significance. Its relevance is particularly pronounced in light of the numerous upcoming lunar missions that have been announced.

Keywords: lunar communication ; lunar surface propagation ; lunar propagation channels

1. Introduction[1][1]

In October 1958, the National Aeronautics and Space Administration (NASA) commenced its operations and started progress toward the landing of a human on the moon in the 1960s through a project called Apollo, which involved astronauts orbiting the moon and landing on its surface between 1968 and 1972 . When Neil Armstrong and Buzz Aldrin, the Apollo 11 astronauts, took their lunar walk on 20 July 1969, it became one of the most significant events in the history of the world [1][1]. In the year 2004, President Bush entrusted NASA with the responsibility of overseeing space exploration efforts and being in control of the following: 1. The return of humans to the moon. 2. The development of advanced knowledge, technologies, and infrastructures. 3. Enabling human presence across the solar system. 4. Encouraging the participation of international and commercial organizations in this project. 5. Initiating missions involving humans and robotics to the moon . NASA conducted comprehensive architecture studies to shape lunar mission strategies. The Lunar Architecture Team had two phases of research in 2006–2007 to outline lunar surface systems and infrastructure plans. Simultaneously, NASA's Science Mission Directorate initiated a lunar science robotic mission strategy. The inaugural undertaking involved a compact orbiter focused on atmospheric and dust science, scheduled for a 2011 launch. Subsequent missions aimed to deploy mini-landers for geophysical studies, with the initial pair planned for a 2014 launch . Afterward, America started on a groundbreaking journey in space exploration, science, and technology, poised to delve deeper into the moon's mysteries than ever. This ambitious endeavor is known as the Artemis program, named after Greek god Apollo's twin sister, the moon goddess. Launched in 2017, Artemis entails a series of continuous lunar missions under NASA's guidance, aiming to comprehensively uncover the moon's secrets through a combination of scientific inquiry and human exploration objectives . China launched the Chang'e-5 (CE-5) lunar exploration mission in 2020. The Lunar Regolith Penetrating Radar (LRPR) is a high-resolution imaging radar installed on the CE-5 lander to probe the lunar regolith's thickness and fine structure in the landing region. The radar's purpose Is to investigate the electromagnetic properties, mineral content, structure, creation, and development of the lunar regolith. Characterizing the lunar regolith with the LRPR can aid drilling and sampling operations . Very recently India achieved a monumental feat by executing a historic landing at the lunar south pole as part of the Chandrayaan-3 mission . The Vikram lander touched down on the moon with the primary objective of locating water-based ice, crucial for future human habitation and interplanetary missions. Equipped with five scientific instruments, it aims to analyze the lunar surface, atmosphere, and subsurface tectonic activity. There is also a burgeoning interest in lunar communication systems to facilitate data transfer among lunar assets and establish reliable communication with Earth stations . Among these, the most recent endeavor is the Emirates Lunar Mission (ELM), an initiative spearheaded by the Mohammed Bin Rashid Space Centre (MBRSC) . This ambitious project aims to conceive and actualize the UAE’s inaugural robotic lunar mission, with the Rashid rover playing a pivotal role in this groundbreaking venture. The Rashid rover was launched in December 2022 from Cape Canaveral Space Force Station in Florida, marking a historic moment in the UAE’s space exploration journey. Regrettably, during its landing, the lander could not achieve a soft landing, consequently preventing it from carrying out its intended operations. Nevertheless, the Rashid rover is part of a series of rovers that MBRSC plans to send for exploration on the moon and other celestial bodies in the future. The Rashid rover is outfitted with advanced cameras—a high-resolution camera for detailed imagery, a microscopic camera for capturing fine particulars, and a thermal imaging camera. Additionally, the rover is equipped with a specialized Langmuir probe, intended for delving into the mysteries of lunar plasma and unraveling the enigma behind the moon’s notably adhesive dust. Its primary mission was to investigate the lunar surface, assess mobility on the moon’s terrain, and explore the interplay between diverse surface materials and lunar particles.

Lunar missions have played a pivotal role in advancing our understanding of the moon and its surroundings, facilitating groundbreaking scientific research and paving the way for future lunar expeditions, including crewed missions. These missions have relied on a complex network of communication to ensure the successful exchange of critical data, instructions, and insights between Earth and lunar mission components. The significance of lunar communication becomes evident when we consider the multifaceted nature of lunar missions. These missions have encompassed a wide range of objectives, from exploring the lunar surface’s geological and topographical features to conducting experiments and observations that contribute to our knowledge of the moon’s history and potential resources. Moreover, lunar missions have acted as precursors to human exploration, making the establishment of reliable communication pathways of paramount importance. In this context, various communication pathways have been established, each tailored to the specific needs of lunar missions. These pathways include Earth-to-lunar relay satellites, which serve as essential intermediaries for transmitting signals between Earth and lunar mission components. Additionally, direct communication links between Earth and lunar landers or the lunar surface itself have been vital for data transfer and real-time operations. Furthermore, lunar surface-to-lunar surface communication has played a pivotal role in coordinating activities, sharing scientific findings, and enhancing mission efficiency.

2. Lunar Surface Propagation Path Loss Models

To enhance surface exploration, multi-robot systems are being extensively researched. Accordingly, understanding the operational environment is crucial for accurate radio propagation modeling due to differences between lunar and terrestrial conditions. While propagation models for signal strength are well-established on Earth, their suitability for lunar sites requires careful evaluation due to the unique lunar conditions . Different approaches to propagation modeling can be seen in the literature. The very well-known approach is that of NASA , which presented the application of an adapted Longley–Rice model for irregular terrains along with digital elevation data that accurately represent a real lunar location. This model is well suited to estimating path loss deviation from theoretical attenuation over a reflecting surface. This model also validated the field data collected during the Apollo project. This approach also enables the estimation of radio frequency (RF) path loss across the lunar landscape. Another approach was to introduce lunar propagation models that take inspiration from various established terrestrial communication models such as Fresnel zones, the free-space path loss model, and the irregular terrain model including reflection and diffraction due to irregular terrains . This approach was used to formulate a radio propagation model tailored to the lunar environment, specifically designed for micro-rovers equipped with low-height antennas. By utilizing this newly developed model alongside the Digital Elevation Model of the Apollo 15 Mission’s landing site, a series of simulations were conducted to forecast the feasible communication range and the quality of links for three different micro-rovers. Another approach is to utilize the free-space model, two-ray model, and spherical diffraction model to estimate radio attenuation on the lunar surface . This model can accurately predict the link budget in lunar surface communication. The results were close to that of the model predicted in . In , a solution for predicting path loss in lunar communication when encountering obstacles is outlined. This method simplifies transmission loss across the lunar surface into four typical scenarios based on lunar surface irregularities and obstacle shapes. The analysis accounts for free-space transmission loss, ground proximity loss, diffraction loss, and antenna gain. Additionally, data from the Apollo project were incorporated into this study, demonstrating that their accuracies align well with the model presented in . Moreover, a lunar wireless model was developed in . In this proposed model, the Digital Elevation Model from four distinct lunar sites is employed. These models were generated through measurements taken by the Terrain Mapping Camera, which was part of Chandrayaan-1, a recent lunar mission conducted by India. A lunar wireless mode examines all potential occurrences and signal degradations relevant to the wireless sensor network deployed on the lunar surface and anticipates minimal diffraction loss compared to the primary factors of direct path attenuation and multipath signal reflections for the specific intended usage. Given the primary objective of establishing unobstructed line-of-sight communication between transmitting and receiving units, this level of loss was disregarded. In , there was an attempt to develop a propagation analysis incorporating terrain characteristics, frequency considerations, and antenna height. The aforementioned models did not directly account for these factors. Given that reflections and diffractions are the dominant mechanisms in terrain-specific effects at higher frequencies, it becomes crucial to realistically incorporate these effects. In this context, the geometrical theory of diffraction (GTD) was employed, allowing for the consideration of reflections and diffractions from three-dimensional (3-D) lunar terrain, including craters. The study yielded promising results, highlighting the impact of antenna heights, frequency, and lunar ground material on antenna performance and path loss. Notably, it was observed that path loss increased with higher frequencies. There is an ongoing need for improved path loss models, especially at higher frequencies. This area of research remains an open question, with numerous researchers striving to introduce innovative approaches for crafting a more realistic model that encompasses the real terrain effects found in the lunar environment. **Table 1** summarizes the propagation models reported so far.

Table 1. Summary of lunar propagation models.

Ref	Models Considered						
	Free-Space	**Freznel**	**Reflection**	**Two-Ray**	**Diffraction**	**Irregular Terrain**	**Multipath**
	✓	✓			✓	✓	
					✓	✓	
	✓			✓	✓		
	✓			✓	✓		
	✓					✓	✓

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