Postprint: Research on Lunar-Based Low-Frequency Antenna Technology

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Date: 2017-09-26T00:00:00+00:00

Abstract

Lunar-based low-frequency antennas have become one of the research hotspots in the field of radio astronomy technology in recent years. Due to the shielding effect of the Earth’ s ionosphere, radio waves with frequencies below 30 MHz are difficult to observe effectively from the ground. The lunar surface, particularly the far side of the Moon, has been proven to be an excellent location for low-frequency radio astronomy observations. Through investigating the current research status of lunar-based low-frequency antennas both domestically and internationally, this paper expounds on the advantages of lunar-based low-frequency antennas over ground-based low-frequency antennas for low-frequency radio observations, introduces the current state of research on lunar-based low-frequency antennas worldwide, and presents in detail the crossed dipole array antenna design scheme of the Key Laboratory of Lunar and Deep Space Exploration, National Astronomical Observatories. The array antenna was modeled and simulated using the electromagnetic simulation software HFSS, and the simulation results are presented. The simulation results demonstrate that the crossed dipole array antenna exhibits relatively high gain, good directivity, and the capability to resolve the direction of arrival of incoming waves. Finally, the key technologies for lunar-based low-frequency antennas are introduced. To meet the design requirements of miniaturization, lightweight, and foldability for spacecraft payloads, a tape measure-type design approach for the crossed dipole array antenna element is proposed.

Full Text

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Volume 14, No. 1, January 2017
Astronomical Research & Technology

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Abstract: Low-frequency radio astronomy from the Moon has gained increasing research attention in recent years. Due to the shielding effect of Earth’ s ionosphere, electromagnetic waves below 30 MHz are very difficult to detect from ground-based antennas, and radio waves below 5 MHz cannot be received at all. The lunar surface, particularly the far side of the Moon, provides an ideal environment for low-frequency radio observations. This paper presents the advantages of lunar-based low-frequency antennas compared to their Earth-based counterparts, reviews international research progress, and introduces the design and simulation results of a lunar low-frequency antenna developed by the Key Laboratory of Lunar and Deep Space Exploration at the National Astronomical Observatories. The proposed cross-dipole antenna array demonstrates relatively high gain and directional resolution capability. Key design technologies including miniaturization, active antenna implementation, and ultra-wideband operation are discussed. Finally, future development trends for lunar low-frequency antennas are outlined.

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1. Introduction

Cosmic low-frequency electromagnetic radiation can reveal phenomena inaccessible at other frequencies, including low-energy cosmic ray particles, thermal environments of discrete radio sources, searches for Earth-like planets, large-scale structure distribution, coherent radiation from plasma processes in galactic and extragalactic objects, low-frequency and very-low-frequency pulsar radiation, gas distribution in the interstellar medium, solar coronal mass ejections, and radio bursts [1-3]. However, electromagnetic signals below 30 MHz cannot penetrate Earth’ s ionosphere to reach the ground, leaving this portion of the spectrum largely unexplored. Conducting low-frequency radio observations, particularly below 1 MHz to 10 kHz, requires overcoming the limitations imposed by Earth’s ionosphere. While planetary landers and space probes equipped with radio antennas have been used for such studies, opening this new radio window offers significant opportunities for space science and potential major discoveries [4-5].

2. Advantages of Lunar-Based Low-Frequency Antennas

2.1 Natural Shielding from Interference

Earth-based radio telescopes suffer severe interference from artificial electromagnetic signals. Numerous broadcast stations and communication transmitters continuously emit radio waves that, despite attenuation over distance, remain strong enough to disrupt low-frequency observations even in remote radio-quiet zones. In contrast, lunar-based antennas are naturally shielded from terrestrial noise because Earth’ s ionosphere confines artificial electromagnetic emissions.

Additionally, lunar craters and the Moon itself block low-frequency electromagnetic noise generated by Earth' s ionosphere through interactions with solar wind particles. This shielding enables lunar antennas to detect faint cosmic low-frequency signals with high sensitivity [6].

3. International Research Progress

3.1 Dark Ages Lunar Interferometer (DALI)

The Dark Ages Lunar Interferometer, funded by NASA, is a lunar-based radio interferometer operating at 30-200 MHz with a maximum baseline of 10 km. The project has completed ground-based prototype development but has not yet been deployed on the Moon. NASA aims to install it in radio-quiet lunar craters on the far side or at the lunar south pole. The basic radiating elements are planar printed crossed dipoles embedded in polyimide film strips. Each strip contains multiple dipoles arranged in a line, with 100-meter spacing between adjacent strips. The 20-micron-thick polyimide film protects against lunar dust contamination. Each station comprises numerous such strips arranged in a cross pattern, forming a complete lunar interferometer array [13].

3.2 Radio Observatory on the Lunar Surface for Solar Studies (ROLSS)

Also developed by NASA, ROLSS is a low-frequency array for solar studies operating at 1-10 MHz. The array features four arms, each 1,000 meters long, with expanded electrically small dipole antennas arranged logarithmically to provide Fourier spacing. Each dipole measures 14 meters in length. The low-frequency signals are amplified by low-noise amplifiers at each antenna, transmitted via microwave transmission lines to central electronics, filtered, and then digitized. The entire antenna system is wrapped in polyimide film to prevent dust contamination. The four arms are rolled up for launch and deployed robotically or by astronauts from a central lander, requiring favorable lunar surface conditions [14].

3.3 Lunar Array for Radio Cosmology (LARC)

LARC is another NASA-funded lunar radio astronomy project designed to mitigate Earth' s low-frequency interference by placing antennas in radio-quiet valleys on the far side. Each element consists of a helical antenna with a back cavity, operating at 45-90 MHz. The helices are compressed flat before deployment and pop up into shape when deployed. The antenna achieves 13.9 dBi gain with good axial symmetry and low sidelobes below -12.5 dB. Each Self-Tending Array Node and Communications Element (STANCE) forms a triangular array of seven helical antennas with identical polarization. The central electronics package contains low-noise amplifiers, ADCs, and thermal control systems. Fiber optic connections prevent harmonic interference from microwave communication leakage [15].

3.4 Chang' e-2 Lunar-Based Very Low Frequency Interferometer

Proposed by the National Astronomical Observatories for China' s Chang' e-2 lunar landing mission, this very low frequency interferometer consists of two dipole antenna groups. One group is fixed to the lander (stationary after landing), while the other is mounted on the rover. As the rover moves, continuous interferometric measurements are performed. The VLF signals are Nyquist-sampled and transmitted to Earth for post-processing using interferometric and phased-array techniques. Simulations show angular resolution better than 4.98 meters when observing at 10 MHz with optimal antenna separation.

4. Design and Simulation of Lunar Low-Frequency Antenna

4.1 Array Antenna Design

The Key Laboratory of Lunar and Deep Space Exploration at the National Astronomical Observatories has developed a lunar low-frequency antenna design. Considering the lunar deployment environment, a sparse array configuration was adopted to achieve high resolution with minimal elements. A 2$×$2 square array of cross-dipole elements was modeled and simulated in Ansoft HFSS, with adjacent element spacing optimized for performance.

4.2 Simulation Results

When all array elements receive signals in phase, the antenna array at 30 MHz exhibits maximum gain perpendicular to the antenna plane (zenith direction). By adjusting the phase relationship between elements, the main beam can be steered to the E-plane at 30° with a gain of 8.15 dBi [FIGURE:8(a)], or to the H-plane at 45° with a gain of 6.35 dBi [FIGURE:8(b)]. The array achieves 8.33 dBi maximum gain when steered to the H-plane [FIGURE:8(c)]. The results demonstrate high gain, directional capability, and the ability to resolve wave arrival directions.

5. Key Technologies

5.1 Antenna Miniaturization

Low-frequency radio wavelengths are long, requiring large antenna elements. However, lunar deployment demands compact, lightweight, and foldable designs. The European lunar antenna employs a tape-measure structure where dipole arms are coiled during launch and spring open to 2.5 meters upon deployment. This design folds to just 2 cm × 4 cm × 4 cm with a total mass of only 0.56 kg, meeting launch payload constraints. The lunar microgravity environment ensures minimal deformation after deployment, while the vacuum prevents weather-related distortion.

5.2 Active Antenna Technology

To receive cosmic low-frequency signals across extremely wide bandwidths, active antenna technology is essential. Traditional passive antennas struggle with bandwidths spanning tens or hundreds of octaves. Active antennas incorporate low-noise amplifiers that significantly expand the operating bandwidth while enabling reception of faint signals across a broad frequency range.

5.3 Ultra-Wideband Technology

The ultra-wideband requirement poses challenges because antenna impedance varies with frequency while feedline characteristic impedance remains constant (typically 50 Ω). This mismatch causes energy reflection and performance degradation. Tunable broadband impedance matching circuits, analogous to radio tuning circuits, can maintain low mismatch loss across wide frequency ranges.

6. Future Development Trends

Current efforts focus on lunar ionosphere detection using small arrays with simple dipole or monopole elements that can be remotely deployed. These small arrays have limited sensitivity and resolution, as exemplified by the European lunar antenna. Building on this experience, future development will progress toward large-scale arrays with thousands of elements and extended baselines, such as DALI, ROLSS, and LARC. These major astronomical infrastructures will require robotic or astronaut-assisted construction and will enable resolution of closely spaced celestial sources at great distances.

7. Conclusion

This paper has highlighted the advantages of lunar-based low-frequency antennas over ground-based systems, reviewed international research progress, and presented design and simulation results from the National Astronomical Observatories' Key Laboratory. The proposed cross-dipole array demonstrates high gain and directional resolution. Key technologies including miniaturization, active antenna design, and ultra-wideband operation were discussed. Future trends indicate progression from small exploratory arrays to large-scale interferometric facilities, which will open new scientific windows for radio astronomy.

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Note: Figure translations are in progress. See original paper for figures.