Ground-Based Radar Observations of the Moon in China: Current Status and Research Progress (Postprint)

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Abstract

Ground-based radar astronomical observations can provide information regarding the topography, physical characteristics, orbital dynamics, and other properties of solar system celestial targets. This article focuses on the principles, methodologies, and scientific significance of lunar observations utilizing ground-based radar astronomical technology, and presents preliminary ground-based radar lunar observation experiments conducted in the UHF and X bands, based on China’ s existing deep-space radar uplink facilities, radio telescope capabilities, and incoherent scatter radar systems. Through signal processing of lunar reflected echoes, parameters such as delay and Doppler shift were obtained, yielding consistent lunar surface radar reflectivity correlated with near-surface material density, as well as lunar left- and right-handed circular polarization ratios that reflect the lunar near-surface structure at scales comparable to the wavelength. The data processing experience accumulated in this study will provide a technical foundation for China’ s ground-based radar astronomical observation research in areas such as asteroid early warning and planetary ephemerides.

Full Text

Preamble

The Status and Research Progress of Ground-Based Radar Observations of the Moon in China

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Abstract: Ground-based radar astronomical observations can provide information on topography, physical characteristics, orbital dynamics, and other properties of solar system bodies. This paper focuses on the principles, methods, and scientific significance of lunar observations using ground-based radar astronomy techniques. We introduce preliminary UHF and X-band ground-based radar lunar observation experiments conducted using China’ s existing deep-space radar uplink facilities, radio telescopes, and incoherent scatter radar systems. Through signal processing of lunar reflected echoes, we obtained parameters such as time delay and Doppler shift, derived consistent lunar surface radar reflectivity related to near-surface material density, and determined the lunar circular polarization ratio, which reflects near-surface structures at wavelength scales. The data processing experience accumulated in this work will provide a technical foundation for China’ s future ground-based radar astronomical observations, including asteroid early warning and planetary ephemeris research.

Keywords: ground-based radar; Moon; radar albedo; circular polarization ratio

Radar can actively transmit electromagnetic waves to detect and track space targets. By controlling the transmitted signal, it can study the size, shape, rotation period, and other characteristics of solar system bodies, making it one of the most effective techniques for investigating topography, physical properties, and orbital dynamics. Current radar detection technologies can be categorized as ground-based, spaceborne, in-situ, and space-ground joint observations, each with distinct features and advantages. Ground-based observation places radar systems on Earth to observe solar system bodies, utilizing large-aperture antennas for transmission and reception. This approach offers short observation cycles, cost-effectiveness, convenience, and high repeatability. Spaceborne observation mounts radar on satellites launched into orbit around target bodies, providing wide coverage and high precision but at greater cost and with longer observation cycles. In-situ observation deploys radar on planetary rovers landed on celestial surfaces, enabling high-resolution subsurface geological structure mapping with high precision, though limited in coverage area. Space-ground joint observation separates transmitting and receiving equipment between spaceborne and ground-based platforms, combining the advantages of both while reducing payload weight, though data processing is more complex and resolution may decrease. Ground-based radar remains the primary means for future solar system body exploration due to its low cost and high resolution.

The Moon, Earth’ s nearest celestial neighbor, has long been the preferred target for human astronomical and space exploration activities. It is also the earliest and most frequently observed body using ground-based radar. In January 1946, a U.S. Navy ground station transmitted electromagnetic waves toward the Moon and received echoes after less than 3 seconds—the first time humans detected solar system bodies using ground-based radar. Radar offers unique advantages for lunar exploration: it operates independently of illumination and weather conditions, enabling observation of permanently shadowed regions at the lunar poles and impact craters. Synthetic aperture techniques enable lunar surface topographic mapping and imaging. Furthermore, based on electromagnetic wave penetration and polarization characteristics, analysis of backscattered echoes can retrieve subsurface properties such as regolith thickness, dielectric constant, and geological structure, as well as detect potential water ice. However, due to Earth-Moon geometry, ground-based radar can only observe the Earth-facing hemisphere.

Ground-based radar has yielded fruitful scientific results in lunar topography mapping, regolith thickness inversion, and water ice detection. The United States leads in ground-based radar astronomy with robust infrastructure and signal processing methods. Major U.S. observatories including GSSR (Goldstone Solar System Radar), Arecibo, and Green Bank have dominated ground-based radar observations of solar system bodies. Table 1 lists key parameters of major U.S. ground-based radar systems. In contrast, China’ s application of radar technology for celestial body detection remains in its infancy. The Lunar Penetrating Radar (LPR) onboard Chang’ E-3 represented China’ s first use of radar technology for extraterrestrial body detection and humanity’ s first in-situ radar observation of an extraterrestrial body. However, China currently lacks a dedicated ground-based radar system for observing the Moon and other solar system bodies. Nevertheless, existing domestic facilities—including deep-space network radar systems, the Qujing incoherent scatter radar in Yunnan, and China’ s large-aperture radio telescope network—already possess the capability to transmit and receive lunar detection signals. By developing data processing methods for ground-based radar observations, we can currently conduct experimental observations and scientific research on the Moon and other bodies, complementing satellite-based exploration approaches, significantly advancing China’s solar system body detection and planetary science research, and playing a crucial role in near-Earth asteroid monitoring and early warning. Ground-based radar astronomy also enables satellite protection and monitoring of potentially hazardous space objects.

1 Principles and Methods

Radar target detection and feature extraction is essentially a data processing procedure based on transmitted and received echo signals. Radar transmits electromagnetic waves of specific frequency bands and modulation forms; these waves reflect upon reaching the target, and the reflected portion is received as echo signals containing the target’ s electromagnetic scattering characteristics. Through complex echo data processing, we can invert the target’ s electromagnetic scattering properties at specific frequencies and reconstruct its shape and structure. Radar thus satisfies diverse requirements for solar system body observations, obtaining high-resolution topographic distributions, dielectric constants, and geological structures. Since surface geometric structures and physical properties produce different polarization characteristics, transmitting specifically modulated polarization signals and extracting multi-dimensional information including echo delay, Doppler shift, and polarization enables precise determination of target distance, velocity, size, shape, geometry, and physical properties. Moreover, radar electromagnetic waves possess penetration capability for subsurface structure detection. However, ground-based radar signals attenuate rapidly, with intensity inversely proportional to the fourth power of distance, requiring high transmission power and sensitive reception systems. Additionally, ground-based radar data processing algorithms are complex, requiring precise prior knowledge of the observed body' s relative motion.

1.1 Echo Time Delay and Range Resolution

Radar echo signal time delay reflects the transmission distance from transmission to reception, with the relationship shown in Equation (1). By studying delay relative to reflected signals, we can determine target distance and calculate celestial ephemerides.

$$\text{delay} = \frac{2R}{c} \quad (1)$$

where c is electromagnetic wave propagation speed and R is transmission distance. For spherical objects, the vertex nearest the radar returns the shortest time, forming different range rings centered on this point. Radar range depth information can invert target radius, while range gate information characterizes surface features. For wideband radar, range resolution capability relates to transmitted signal bandwidth—greater bandwidth yields higher resolution. Range resolution is calculated as:

$$\rho_r = \frac{k_r c}{2B} \quad (2)$$

where B is radar transmitted signal bandwidth and k_r is the main lobe broadening coefficient caused by windowing during range compression. Since natural bodies like the Moon are large-scale, high range resolution is not required, and transmitted pulse width can directly achieve different range scene resolution. In this case, range resolution is calculated as:

$$\rho_r = \frac{c\tau}{2} \quad (3)$$

where τ is radar transmitted pulse width.

1.2 Echo Doppler Frequency

When relative motion exists between the target body and ground-based radar, the received echo signal frequency shifts—this shift is called Doppler frequency. Doppler frequency directly reflects the target' s radial velocity. For bistatic systems, Doppler frequency f_d can be calculated from the target' s distance change rate relative to the transmitting antenna $\dot{R}_t$ and receiving antenna $\dot{R}_r$ as shown in Equation (4), where f_0 is the radar transmitted signal carrier frequency.

$$f_d = -\frac{f_0}{c}(\dot{R}_t + \dot{R}_r) \quad (4)$$

Different lunar regions have different distances from the Moon' s rotation center, resulting in different rotational linear velocities and projected velocities along the radar line-of-sight, producing different Doppler frequencies. Lunar radar azimuth imaging exploits these differences for azimuth resolution. Echo signal Doppler spectral broadening contains information about target structure and rotation. Lunar echo signal spectral broadening can be roughly estimated theoretically as:

$$\Delta f_d = \frac{4\pi D\theta}{\lambda T_{rot}} \quad (5)$$

where D is Earth-Moon distance in meters, θ is beam width in radians, λ is signal wavelength in meters, and T_{rot} is lunar rotation period in seconds.

1.3 Echo Amplitude Characteristics

According to the radar equation, the amplitude P_r of received lunar reflected echoes relates to distance, transmission power, antenna gain, and other factors, with distance having the greatest impact. The radar equation is:

$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi R^2)^2} \quad (6)$$

where P_t is transmission power, G_t is transmitting antenna gain, A_r is receiving antenna effective aperture, and σ is the radar cross-section of the illuminated lunar surface region, where $\sigma = 4\pi\hat{\sigma}A_{ill}$, $\hat{\sigma}$ is radar albedo, A_{ill} is the illuminated area, and R is the distance from transmitting antenna to the Moon.

From actual received echo energy and Equation (6), we can invert radar albedo $\hat{\sigma}$, which relates to lunar surface material properties. Thompson et al. at Arecibo Observatory found significantly enhanced echoes at fresh lunar crater rims, while Schaber et al. studied lava flows within basins based on anomalously low radar reflectivity in Mare Imbrium.

Dielectric constant effectively characterizes the electrical properties of insulating materials or dielectrics. Lunar dielectric constant can be measured directly from lunar samples or estimated from radar albedo. Dielectric constant values can infer physical properties of the medium layer and important information such as water ice presence, enabling understanding and interpretation of lunar geological structural features. Two parameters control the dielectric constant of layered media: material composition (chemical, mineral, water content, and physical state) and material density. Water ice exhibits low dielectric constant values (typically 3.1), while magmatic rocks have relatively high values (typically 8). Large quantities of water ice in layered media result in lower surface reflectivity compared to dry, dense rock layers. Low-density media can also produce small effective dielectric constants, making complementary datasets crucial for robust interpretation.

1.4 Echo Polarization Characteristics

Analyzing radar signal polarization characteristics enables deeper understanding of lunar surface and near-surface properties, including potential water ice presence and surface roughness. For continuous circularly polarized waves, reflected energy distributes across polarization directions, with reflected polarization related to surface structures at wavelength scales.

Traditional ground-based radar observations typically transmit left- or right-hand circularly polarized (LCP/RCP) electromagnetic waves. Reflection from an ideally smooth planar surface reverses the circular polarization. In practice, most echoes contain both specular and diffuse components, and same-polarization signals are also received due to secondary reflections. Polarization degree is typically described by the ratio of same-sense to opposite-sense components. Using received electromagnetic echo polarization radiation energy, circular polarization ratio (CPR) is calculated as $\mu_c = S_{SC}/S_{OC}$, where "SC" represents echo polarization direction same as transmitted wave, "OC" represents opposite polarization, S_{SC} is total received same-sense polarization echo energy, and S_{OC} is total opposite-sense polarization echo energy. μ_c measures lunar surface roughness at wavelength scales—structures (such as rocks) comparable to radar wavelength. Larger μ_c indicates rougher surfaces.

In ground-based lunar radar detection, simultaneously receiving left- and right-hand circularly polarized echoes from the lunar surface makes CPR an important observable. CPR relates not only to radar configuration (frequency and incidence angle) but also to lunar surface slope, roughness, rock size and abundance, regolith dielectric constant, thickness, and potential polar water ice content. Among all parameters affecting radar echoes, incidence angle is most significant. Generally, larger incidence angles correspond to larger CPR values. Mean lunar surface CPR ranges between 0.4-0.5. Calculating polarization ratios for each spectral domain point, combined with range-Doppler matrices, enables localization of smooth and rough regions. Figure 1 [Figure 1: see original paper] shows Arecibo ground-based radar transmission with Green Bank 100m radio telescope (GBT) reception of lunar south polar CPR map at 70 cm wavelength. Radar shadow regions are set to zero CPR, with values ranging from 0.5 (black) to 1.1 (white) across the region.

Since CPR correlates with surface rock abundance, Figure 1 can be used to deduce polar regolith rock abundance characteristics. Low-CPR halos appear around craters Zucchius, Hausen, Moretus, and Schomberger, indicating low rock content in ejecta from these regions.

1.5 Lunar Water Ice Detection

Scientists long believed the Moon contained no water or water ice, and various detection methods seemed to confirm this. However, the search for lunar water ice has never ceased, with radar playing an important role. Radar systems transmit electromagnetic waves independently of solar illumination, enabling direct detection of permanently shadowed polar craters to determine potential water ice presence.

Water ice volatiles exhibit total internal reflection properties that preserve electromagnetic wave polarization, resulting in elevated CPR values (potentially >1). Frozen volatiles also have lower transmission loss than silicate rocks, producing higher average reflectivity, enhanced backscatter, and greater echo energy—water ice reflects more electromagnetic waves than lunar rocks. Lunar silicate rocks scatter waves in all directions, with some energy not received by ground antennas. These differences in polarization and energy characteristics enable discrimination between regolith and water ice. In 1992, Stacy et al. at Cornell University used Arecibo S-band radar at 125-meter spatial resolution in dual-polarization mode to search for extensive lunar water ice by comparing target region echo characteristics with water ice signatures. Results found no regions >1 km^2 with high radar backscatter cross-section and high CPR, indicating no extensive water ice deposits in lunar polar regions.

While water ice can cause scattering effects, other mechanisms (surface roughness, secondary reflections) can also explain increased CPR in lunar polar regions. Elevated CPR in some permanently shadowed areas may indicate dispersed water ice or simply surface roughness. Additionally, polar water ice may exist as dispersed ice-regolith mixtures (“dirty ice”) that cannot be resolved if radar resolution exceeds the patch size—improving radar resolution is a future challenge. Comprehensive analysis of multi-dimensional lunar data is needed to address the scientific question of lunar water ice existence.

1.6 Regolith Thickness Inversion

The lunar subsurface includes multiple layers: regolith, ejecta, and bedrock. Lunar regolith broadly refers to all weathered materials covering lunar bedrock, including rocks several meters in diameter. Without an atmosphere, long-term exposed regolith receives direct solar wind injection (high-energy particle streams), enriching it with He-3 resources. As a potential fuel for controlled nuclear fusion, He-3 could become an important raw material for long-term human energy needs, making regolith thickness research highly significant. Researchers have observed the Moon at different wavelengths and using different detection modes to obtain regolith thickness distributions, with ground-based radar technology applicable for regolith thickness inversion using high-resolution topographic data, surface roughness, rock size and abundance, and regolith dielectric constant as inputs.

Shkuratov et al. used Arecibo 70-cm wavelength ground-based radar observations of the lunar nearside combined with spectral data on iron and titanium distribution to produce the world' s first lunar nearside regolith thickness distribution map. Results indicated average regolith thicknesses of 5 meters in maria and 12 meters in highlands (excluding highland regions with kilometer-scale megaregolith). In 2011, Fa Wenzhe et al. used high-resolution Arecibo ground-based radar data with a vector radiative transfer theory-based scattering model to determine maria regolith thickness of ~5 m and highlands thickness >10 m.

1.7 Lunar Imaging and Topographic Studies

During the Cold War, the U.S. and Soviet Union competed in lunar exploration, making lunar landform and topography research urgent and critical for landing site selection. Ground-based radar became the preferred method for lunar topographic mapping due to its advantages and contemporary technical limitations. Ground-based radar lunar topographic mapping was primarily conducted during the 1960s-70s, with Arecibo' s lunar radar imaging results establishing the foundation for radar lunar topography detection. While ground-based radar' s value for mid-low latitude lunar nearside mapping has decreased, permanently shadowed regions at the lunar poles remain inaccessible to visible-light detection. Microwave observations are unaffected by solar illumination or weather, enabling ground-based radar mapping of lunar polar topography, particularly in permanently shadowed regions.

Ground-based lunar imaging applies inverse synthetic aperture radar technology to astronomical detection. The principle is illustrated in Figure 2 [Figure 2: see original paper]: ground-based radar transmits electromagnetic signals, and coherent accumulation of echo signals from different observation times—enabled by Earth rotation, lunar rotation, and lunar revolution—achieves high azimuth resolution. Range-Doppler processing of received echoes produces lunar radar images. Coherent echo accumulation depends on precise estimation and compensation of relative radar-Moon motion components. With prior knowledge of relative motion, motion compensation components can be constructed directly to achieve lunar Range-Doppler imaging.

Although ground-based radar can only image the Earth-facing hemisphere rather than the entire Moon, it offers cost-effectiveness, short observation cycles, and high repeatability. Ground-based radar remains the primary means for future lunar topography and polar exploration due to its low cost and high resolution. The goal is continuously pursuing higher-resolution lunar topographic images. Figure 3 [Figure 3: see original paper] shows the highest-resolution (20 meters/pixel) lunar south polar topography map obtained by NASA’ s Goldstone Solar System Radar in 2008—far exceeding ground-based optical telescope resolution and even surpassing Chang’ E-1 CCD camera resolution (120 m).

2 Observational Experiments

Ground-based solar system radar is a high-power system transmitting selected-band electromagnetic waves to solar system bodies, which reflect off the surface and are received by one or more ground stations. Received signal feature analysis enables scientific research on solar system bodies. China has established comprehensive radar systems for aerospace TT&C, space target surveillance, and intelligence reconnaissance, including the first Qujing Incoherent Scatter Radar (QJISR) in Yunnan. Developing ground-based radar celestial body detection data processing technology enables near-term ground-based radar detection of near-Earth bodies, particularly the Moon with its large reflectivity and strong echoes, complementing other detection methods.

2.1 Bistatic Lunar Detection Experiment Using Kashgar Deep Space Station and Kunming 40m Radio Telescope with Continuous Wave Signals

Based on ground-based radar development experience, deep-space detection radar and deep-space networks are independent yet interconnected, sharing many facilities. Deep-space radar antennas can provide transmission and reception services for deep-space networks, while network antennas can serve as receivers for deep-space radar. A series of bistatic lunar ground-based radar astronomy experiments were conducted using Kashgar deep-space radar station (Ks) and Kunming 40m radio telescope station (Km), with parameters listed in Table 2 . During observations, both the transmitting antenna and the receiving antenna thousands of kilometers away were pointed at the Chang’ E-3 lander location in northern Mare Imbrium, composed primarily of lunar basalt.

The transmitting station antenna emitted X-band continuous wave at 7209.125 MHz using left-hand circular polarization with constant carrier frequency and 200 W transmission power. The radio telescope antenna simultaneously received lunar surface reflected echoes in both same-sense circular polarization (SC) and opposite-sense circular polarization (OC) modes, with two-bit quantization and recording. The X-band beamwidths of Ks station’ s 18m antenna and Km station’ s 40m antenna determined a common illuminated lunar area diameter of 503 km, far smaller than the Moon’ s diameter.

2.2 Lunar Detection Experiment Using Qujing Radar with Pulsed Signal Transmission and Reception

The Qujing Incoherent Scatter Radar transmits high-power electromagnetic waves to high altitudes, receiving weak signals scattered by ionospheric electrons and ions to invert numerous ionospheric plasma parameters including density, temperature, and velocity. This radar offers high power, high antenna gain, and low system noise temperature, with important applications for natural celestial body detection like the Moon (though signal processing and inversion methods differ significantly from ionospheric detection).

Qujing radar is a ground-based pulsed mechanically scanned radar using parabolic antenna and klystron transmitter technology, achieving excellent results in ionospheric and space debris detection since commissioning. It features high power-aperture product, can transmit phase-modulated left-hand circularly polarized waves, and receive right-hand circularly polarized waves, with detailed parameters in Table 3 . A series of preliminary lunar monostatic detection experiments were conducted using program-guided tracking mode with beam center always pointing at the lunar center. Since the Moon’ s angular diameter is 40% of the radar beamwidth, single-pulse detection can cover the entire Earth-facing lunar surface.

3.1 Echo Time Delay

The Qujing Incoherent Scatter Radar beam pointed at the Moon transmitted high-power phase-coded pulses (using 13-bit Barker code, 12 ms pulse repetition period, 30 s code element width). Simple pulse compression and coherent processing of lunar echoes yields echo power at different lunar surface time delay positions. Figure 4 [Figure 4: see original paper] shows the lunar scattered echo power-delay profile received at 02:02 UTC on September 11, 2020, with the red curve representing Qujing radar measurements and the blue curve representing Arecibo radar (68 cm wavelength) measurements. The horizontal axis is time, starting from the radar sub-point (intersection of the radar-Moon center line with the lunar surface) and ending at the lunar limb echo (approximately 11.667 ms relative to start). The vertical axis shows normalized echo power, demonstrating close agreement in amplitude and trend between both instruments. In ground-based lunar observations, radar wave incidence angle varies continuously from 0° at the lunar nearside center to 90° at the limb. Lunar echoes are strongest near the sub-point, decaying rapidly with increasing delay depth then gradually declining. This occurs because near the sub-point, low incidence angles produce quasi-specular reflection, while increasing incidence angles produce diffuse scattering from exposed and buried rocks. Quasi-specular reflection is sensitive to lunar surface slope and Fresnel reflection coefficient, while diffuse scattering depends on wavelength-scale surface roughness, rock density, and chemical composition, with power approximately proportional to $\cos^2\theta_i$, where θ_i is radar incidence angle.

3.2 Doppler Frequency

Since 2019, a series of continuous-wave bistatic lunar experiments have been conducted using China's deep-space stations and radio telescopes. During a one-hour observation beginning at 02:30 UTC on April 26, 2019, actual echo signal Doppler (Figure 5 [Figure 5: see original paper]) agreed well with theoretical values estimated from Equation (4), with ~15 Hz residual differences arising from lunar ephemeris usage and calculation. Echo signal Doppler standard deviation was ~7 Hz, with velocity measurement accuracy related to the bistatic station time-frequency system. Additionally, reflected signal spectral broadening was ~35 Hz, consistent with theoretical spectral broadening estimated from Equation (5).

After compensating for lunar translational motion relative to the radar using lunar ephemerides, we obtained echo spectra at different delays from Qujing radar observations. Combining radar pulse length and lunar delay depth, we divided echoes into 24 intervals and calculated signal spectra for each interval, shown in Figure 6 [Figure 6: see original paper]. The figure displays spectra for six consecutive intervals from top to bottom in different colors, with horizontal axis representing signal frequency and vertical axis representing power spectral density. Interval 1 (blue line in first row of Figure 6) shows the strongest power spectrum amplitude, decreasing sequentially, consistent with echo power decay with delay (see Figure 4). All intervals exhibit identical spectral distribution features: a main characteristic with center frequency -590.5 Hz and 3 dB bandwidth ~5.91 kHz, corresponding to 169.2 s coherence time; additionally, a secondary feature with more gradual spectral transition appears near the main feature, with 3 dB bandwidth ~18.2 kHz and 54.95 s coherence time, particularly evident in Interval 1; finally, two weak spectral features gradually appear with increasing delay depth (see Figure 6, row 4) with center frequencies at -17.33 kHz and 16.14 kHz, 3 dB bandwidth 2.64 kHz, and 378.8 s coherence time. Slight offset between spectral center and zero frequency is preliminarily attributed to errors in translational velocity compensation (~177 m/s in this experiment). Lunar echo spectra contain topographic features (such as average surface slope), requiring further verification.

3.3 Echo Amplitude Characteristics and Radar Albedo

Using echo energy received by the Km antenna and Equation (6), the bistatic lunar experiment using Kashgar deep-space station and Kunming 40m radio telescope yielded radar albedo $\hat{\sigma}_{OC} = 0.06$, considering $SNR_{OC} = 121,000$ over 10-second integration time. This radar albedo value represents the average over a 503 km diameter lunar illuminated area centered on the Chang' E-3 lander location.

Using Range-Doppler imaging technology, we extracted radar albedo for different lunar surface positions from Qujing radar data. Based on time delay resolution (30 s) and coherent integration time (90 s), the minimum planar resolution cell size was calculated as $\Delta x \times \Delta y = 4.5\,\mathrm{km} \times 25\,\mathrm{km}$. Statistical analysis of radar albedo for each cell produced the distribution shown in Figure 7 [Figure 7: see original paper]. The average lunar regolith radar albedo is 0.066, corresponding to a dielectric constant of ~2.8, similar to Arecibo radio telescope (68 cm wavelength) results. Note that since the radar was not finely calibrated during the experiment, these results may contain significant bias; system parameter calibration will be performed subsequently.

Combining Range-Doppler matrices, we calculated radar albedo for each point in the spectral domain. Figure 8 [Figure 8: see original paper] shows the radar albedo map for Tycho crater region (0°-30°E, 0°-30°S), where reflectivity reaches nearly 0.6, significantly higher than the lunar average (0.066). However, due to current north-south hemisphere ambiguity in lunar imaging and poor range and azimuth resolution during the experiment, crater outlines and other geographic information cannot yet be identified. Future upgrades to rubidium clock systems and selection of shorter code widths (e.g., 5 s) are expected to greatly improve imaging quality.

3.4 Echo Polarization Characteristics and Circular Polarization Ratio

In the bistatic lunar experiment using Kashgar deep-space station and Kunming 40m radio telescope, the circular polarization ratio obtained at Km station was $\mu_c = 0.44$, shown in Figure 9 [Figure 9: see original paper]. The Chang’ E-3 landing site in Sinus Iridum is among the Moon’ s flattest regions, with unique geographic location and geological environment, making it a hotspot for lunar science research. Subsequent high-resolution, multi-band observation data interpretation will enhance understanding of Sinus Iridum and its relationship with Mare Imbrium.

3.5 Lunar Imaging

Using Range-Doppler imaging technology and coordinate system transformation, we obtained scattering power for different positions on the lunar nearside in Cartesian coordinates (with rotation axis as z-axis, equatorial axis as y-axis, and x-axis satisfying the right-hand rule). Results plotted in the planetary surface coordinate system are shown in Figure 10 [Figure 10: see original paper], with horizontal axis representing lunar longitude (eastward, range -90° to 90°) and vertical axis representing latitude (northward, range -50° to 50°). Due to low range resolution, imaging near the apparent equator (black stripes) is blurred. The image is approximately symmetric about the apparent equator because the radar beam covers the entire lunar nearside, creating north-south hemisphere ambiguity during imaging—unable to distinguish echoes from northern and southern hemispheres. Comparison with Tycho crater location (in southern hemisphere at 11°W, 43°S, marked with red circle) shows basic coincidence, preliminarily validating Qujing Incoherent Scatter Radar lunar imaging effectiveness.

4 Conclusions and Outlook

Radar detection offers real-time capability and rich measurement information for active, all-weather, all-day space target detection. Starting with Earth' s nearest celestial body—the Moon—we studied ground-based radar astronomical detection data processing methods and successfully received lunar reflected radar signals using China' s existing uplink radar equipment and radio telescope network. Results confirm the feasibility and effectiveness of bistatic radar detection mode combining radio telescopes and deep-space radar for lunar observation. Analysis shows echo spectral SNR and Doppler broadening values consistent with a priori estimates. We obtained circular polarization ratio $\mu_c = 0.44$ and radar albedo $\hat{\sigma} = 0.06$ for the Mare Imbrium region. For the first time, we obtained lunar echo power-delay distribution profiles from Qujing Incoherent Scatter Radar lunar echoes and analyzed basic echo characteristics. Using Range-Doppler imaging technology, we preliminarily extracted radar albedo for different lunar regions, finding an average lunar surface radar albedo of 0.066, and obtained preliminary two-dimensional lunar images. Tycho crater location verification confirmed the effectiveness of lunar imaging methods. These results can validate existing Chinese lunar exploration data and provide important references for lunar base site selection.

China currently operates widely distributed narrowband tracking and broadband imaging measurement radars at different frequencies, and radio telescopes possess high-sensitivity multi-band reception capabilities. In particular, China' s "Sky Eye" FAST (Five-hundred-meter Aperture Spherical radio Telescope) can receive radar echo signals below 3 GHz. Future work will expand multi-band joint detection and data processing technology research between radar uplinks and radio telescopes.

China currently lacks dedicated ground-based radar systems for solar system body observation. Given China' s current lunar exploration status and development, ongoing Mars exploration missions, and future asteroid early warning plans, constructing a ground-based radar observation system is needed—not limited to single body types but capable of detecting multiple solar system bodies. Construction and operation costs for such a system are economical compared to expensive space projects, offering tremendous flexibility and economic advantages. Ground-based radar detection represents a future development direction that will not only serve astronomical research and national strategic needs but also vigorously advance China' s future deep-space exploration and planetary science research.

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