Applications of Ground-Penetrating Radar in Lunar and Deep Space Exploration Postprint

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Abstract

The exploration of the Moon and more distant celestial bodies or space environments represents an important direction for human space activities. Conducting lunar and deep space exploration missions facilitates the study of major scientific questions such as the origin, evolution, and current state of the solar system, as well as the origin and evolution of life, and fosters the development of fundamental and forward-looking disciplines and technologies. Compared with optical and other detection methods, radar possesses advantages such as strong penetration capability, polarization characteristics, and independence from illumination constraints, making it one of the effective means for detecting celestial body properties and playing an important role in human lunar and deep space exploration missions. Electromagnetic waves can penetrate subsurface layers from several meters to several kilometers, and can be used to detect surface dielectric constants, subsurface structures, ionospheres, and water ice of lunar and deep space targets. According to different detection methods, subsurface penetrating radar detection mainly includes three approaches: ground-based radar, orbiter radar, and rover radar. For different scientific objectives, different detection methods each have their own advantages and limitations. This paper reviews the scientific applications of subsurface penetrating radar in the exploration of the Moon, Mars, and asteroids, summarizes the detection missions, parameter designs, working principles, and detection results of various radar scientific payloads that have been deployed or are planned, and prospects the development trends of utilizing subsurface penetrating radar for lunar and deep space exploration in the future.

A Review of Application of Surface Penetrating Radar in the Moon and Deep-Space Exploration

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Abstract: The exploration of the Moon and more distant celestial bodies or space environments represents a crucial direction in human space activities. Lunar and deep-space exploration missions facilitate the investigation of major scientific questions such as the origin, evolution, and current state of the solar system, as well as the origin and evolution of life, while fostering foundational and forward-looking disciplines and technologies. Compared with optical and other detection methods, radar offers distinct advantages including strong penetration capability, polarization characteristics, and independence from illumination conditions, making it an effective tool for probing celestial body characteristics and playing a vital role in lunar and deep-space exploration missions. Electromagnetic waves can penetrate subsurface layers from several meters to several kilometers, enabling detection of surface dielectric constants, subsurface structures, ionospheres, and water ice on lunar and deep-space targets. Based on different detection approaches, surface penetrating radar primarily includes three modes: ground-based radar, orbiter radar, and rover radar. Each approach possesses unique strengths and limitations for different scientific objectives. This paper reviews the scientific applications of surface penetrating radar in the exploration of the Moon, Mars, and asteroids, summarizes the mission parameters, design principles, and detection results of various radar instruments currently in operation and planned for future missions, and discusses future development trends for lunar and deep-space exploration using surface penetrating radar.

Keywords: surface penetrating radar; deep-space exploration; ground-based radar; orbiter radar; rover radar

Deep-space exploration refers to exploration activities that escape Earth' s gravitational field and enter solar system and cosmic space [1]. Since the United States launched the Pioneer lunar probe in 1958, human lunar and deep-space exploration has experienced two peak periods [1]. The first peak occurred from 1958 to 1976, featuring a series of missions to the Moon, Mars, Venus, Mercury, and other bodies, with the most iconic achievement being crewed lunar landing and sample return [1]. In 1994, the U.S. Clementine mission discovered possible water ice on the Moon [2], heralding the second peak period. More countries (ESA, China, India, Japan) formulated and implemented exploration programs, conducting further investigations of the Moon and Mars, achieving soft landing on the lunar far side and conducting rover radar 探测 there. In 2020, ESA, the United States, and China all planned to launch Mars probes to achieve soft landing and surface roving exploration on Mars. Deep-space exploration radar has a long history, offering real-time detection capabilities and all-weather observation of deep-space targets. Surface penetrating radar detection modes primarily include ground-based radar, orbiter radar, and rover radar.

Ground-based radar represents the earliest detection method, with lunar 探测 beginning in 1946, followed by investigations of Venus, Mercury, Mars, and asteroids. Arecibo obtained lunar backscatter data at 70 cm wavelength, which Shkuratov and Bondarenko used to calculate the first map of lunar regolith thickness distribution on the near side [3]. Between 1988 and 1990, Harmon et al. used Arecibo and Goldstone radars for long-term Mars observations, studying the relationship between radar echoes and frequency. Further analysis yielded Mars surface images and investigated decimeter-scale surface roughness [4,5].

Orbiter radar development began relatively later. In 1972, Apollo 17 used ALSE to 探测 portions of the Moon. In 1994, the U.S. Clementine mission studied electromagnetic wave occultation by the Moon and used echo information to analyze the possibility of water ice and other frozen volatiles in lunar polar regions [6]. In 2003, ESA's MARSIS 探测 subsurface and shallow structures, obtaining global 3-5 MHz surface radar echo maps and deriving shallow dielectric constant distribution across Mars [7]. In 2018, the Italian Space Agency announced that MARSIS data analysis revealed a 20 km wide water lake beneath 1.5 km of ice in the Planum Australe region. In 2005, NASA' s Mars orbiter carried SHARAD radar for Mars 探测. In 2019, Nerozzi et al. used SHARAD to discover extensive ice layers at approximately 1500 m depth in Mars' north pole [8]. In 2007, Japan' s KAGUYA LRS observed strong signal reflections from several hundred meters beneath lunar maria on the near side, suggesting reflections from regolith layers covered by hundreds of meters of basaltic rock [9-11]. In 2009, Spudis et al. used Mini-SAR data from India' s Chandrayaan-1 to obtain Stokes parameters of reflected signals, enabling discrimination between volume scattering from water ice and other scattering mechanisms [12].

Affected by delays and cancellations of planetary landing programs, rover radar development stagnated after Apollo 17' s SEP in 1972 until China' s Chang' e-3 landed on the Moon in 2014, once again enabling subsurface 探测 with rover radar. In 2019, Chang' e-4 achieved humanity' s first soft landing on the lunar far side, with its penetrating radar conducting the first rover radar 探测 on the lunar far side. In 2020, China, the United States, and Europe planned Mars landings, with Mars rovers carrying MAPER, WISDOM, and RIMFAX radars respectively, which will play important roles in 探测 Mars subsurface structure and water ice.

Surface penetrating radar for lunar and deep-space exploration has evolved from ground-based to orbiter to rover radar. Radar modes have gradually transitioned from pulse radar to synthetic aperture radar and frequency-modulated radar. Radar has achieved fruitful results in lunar and deep-space exploration, being used to detect planetary surface dielectric properties, subsurface structures, and water ice. With continuous radar technology development, radar 探测 will continue to play a vital role in future lunar and deep-space exploration.

1. Ground-Based Radar

Ground-based radar (surface penetrating ground-based radar for lunar and deep-space 探测) is a high-power active radar observation system that transmits specific frequency electromagnetic waves from ground facilities toward lunar or deep-space targets. When encountering dielectric discontinuities at the target body’ s surface and interior, waves are reflected back and received by ground equipment. Analyzing these received signals enables investigation of subsurface structures and surface dielectric characteristics. Major ground-based radars include the U.S. Arecibo, GSSR (Goldstone Solar System Radar), GBT (Green Bank Telescope), and Sweden’ s LOIS system [3,6,13]. lists the main parameters of these radars.

Ground-based radar was first used for lunar 探测 in 1946, with Schubert and Schaber using it to study lunar impact craters and magma flows in the Mare Imbrium basin [3]. As optical 探测 technology advanced, ground-based radar was replaced by optical methods in well-illuminated lunar regions, shifting focus to poorly illuminated polar shadowed regions [3]. In 2008, NASA used Goldstone radar to obtain lunar south pole topography with 50 times higher resolution than the Clementine orbiter. Shkuratov et al. used Arecibo radar data combined with lunar iron-titanium content to invert dielectric constant distribution and regolith thickness on the lunar near side [14]. Ground-based radar has also been widely applied to Mars, Venus, Mercury, and asteroid 探测 [3]. Researchers selected 86 targets from 1235 potential Earth-like planets discovered by Kepler for GBT radar observation, which will play important roles in exploring extraterrestrial life and habitable planets.

Ground-based radar for surface penetrating 探测 is also an important component of deep-space TT&C networks, playing a vital role in deep-space telemetry and control. As probes travel farther from Earth, signals become weaker, and single antennas can no longer meet data transmission requirements. Forming deep-space TT&C networks by combining existing ground-based radars with other antennas is a primary solution. Deep-space TT&C networks have larger equivalent apertures, significantly improving signal transmission quality and signal-to-noise ratio. The United States, ESA, and China have established their own deep-space TT&C networks, while Russia, Japan, India, Italy, Germany and others have deep-space TT&C equipment but not complete networks [15]. Currently, only the U.S. Deep Space Network can conduct surface penetrating radar 探测; other countries’ networks are primarily for TT&C and lack active surface penetrating radar capabilities [16].

Compared with other 探测 methods, ground-based radar offers distinct advantages: (1) Low cost: construction and maintenance are more economical than space projects. (2) High flexibility: can 探测 multiple deep-space targets. However, disadvantages constrain its development: (1) Complex data processing: relative motion between Earth and deep-space targets due to rotation and revolution must be considered during observation. (2) Weak signals: despite high transmission power, return signals are weak due to vast distances, and cosmic electromagnetic interference makes it difficult to extract useful information from the background.

2. Orbiter Radar

Orbiter radar transmits electromagnetic pulses that penetrate planetary surfaces and subsurface layers. When encountering discontinuities, echo signals are generated and received by the radar antenna. Analyzing these echoes yields geological structure information about planetary subsurface layers. and list the basic parameters of orbiter radars currently in service and planned for future missions.

2.1.1 ALSE

ALSE (Apollo Lunar Sounder Experiment) was a payload on the U.S. Apollo 17 mission launched in 1972, representing humanity’ s first radar 探测 of lunar subsurface structure. Its main objectives were: (1) 探测 lunar subsurface structure; (2) mapping lunar profiles and determining topography; (3) lunar surface microwave imaging; (4) measuring galactic electromagnetic radiation in the lunar environment [17].

ALSE operated at three frequency bands centered at 5 MHz, 15 MHz, and 150 MHz. Electromagnetic waves penetrated the lunar surface and subsurface, generating echo signals when encountering discontinuities. Analyzing these echoes provided subsurface geological structure information. In 1973, R.J. Phillips et al. used ALSE data to determine a maximum 探测 depth of approximately 1 km. ALSE observed two nearly continuous reflectors in Mare Serenitatis and one reflector in Mare Crisium [6,18].

2.1.2 BRE

BRE (Bistatic Radar Experiment) was a bistatic radar carried by the U.S. Clementine orbiter launched in 1994, primarily designed to 探测 possible water ice in lunar polar regions [2]. BRE transmitted electromagnetic waves toward the Moon; when encountering the surface or internal dielectric discontinuities, reflected signals were received by Deep Space Network (DSN) antennas on Earth. Analysis of these reflected signals enabled inversion of lunar surface geological information.

Amplitude and polarization analysis of BRE reflected signals indicated water ice in lunar surface soil. However, Arecibo ground-based radar results showed similar water ice signals even in non-permanently shadowed regions, suggesting BRE’ s water ice signals might result from surface roughness or other factors.

2.1.3 Gassini Orbiter

The Gassini radar was a payload on the U.S. Cassini-Huygens mission launched in 1997. Cassini-Huygens entered Saturn orbit in 2004, with Gassini remaining in orbit around Saturn’ s moons while Huygens successfully landed on Titan [1]. Cassini’ s radar was primarily used to study Titan. Although liquid methane oceans and lakes had been predicted, Saturn’ s thick atmosphere prevented conventional detection methods from observing beneath it. In 2006, Gassini conducted radar 探测 of Titan.

Titan’ s surface is hidden beneath a thick atmosphere. Orbiter radar electromagnetic waves can penetrate this atmosphere, reach Titan’ s surface, and return, enabling study of geological features such as lakes, mountains, and dunes. Cassini radar’ s radiometry mode is a passive mode that determines surface temperature by analyzing Titan’ s self-emitted electromagnetic waves. Its scatterometry mode 探测 surface roughness, providing scientific data for studying Titan’ s methane oceans. The radar also studied Saturn, its rings, and other moons.

2.1.4 MARSIS

MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) was a payload on ESA’ s Mars Express orbiter launched in 2003, primarily used to 探测 Mars subsurface structure and polar ice layers [7,20-23].

MARSIS employs pulse compression mode, performing matched filtering on received signals and correlating them with transmitted signals to narrow echo pulses and concentrate energy. To eliminate sidelobe effects after pulse compression, MARSIS applies Hanning windowing to reference signals. Between 2012 and 2015, MARSIS detected lake-like reflected signals in Mars’ Planum Australe region. Further analysis by the Italian Space Agency in 2018 revealed these signals originated from the interface between glacier and subglacial lake, indicating a 20 km wide liquid water lake beneath 1.5 km of ice cap. However, no other radar including NASA’ s SHARAD has obtained similar signals.

2.1.5 CONCERT

CONCERT (Comet Nucleus Sounding Experiment by Radiowave Transmission) was a radar instrument for ESA’ s 2004 Rosetta mission’ s CNSR (Comet Nucleus Sample Return). Its main objectives were to 探测 comet surface dielectric properties, large-scale structures (10-meter scale), internal small-scale structure distribution, and layered structures [24].

CONCERT’ s mission was to guide the lander to the comet, collect samples, and return them to Earth. Before landing, suitable sites with ice and volatile materials (scientifically valuable) that ensured safe landing and return had to be selected. Therefore, the comet’ s surface structure needed to be 探测 beforehand. One of CNSR’ s primary tasks was using radar to 探测 comet topography and surface structure to select optimal landing sites.

CONCERT’ s principle is based on energy loss and velocity changes during electromagnetic wave propagation, which are closely related to comet material’ s complex dielectric constant, heterogeneity, and radar frequency. Measuring these velocity and energy changes enables inversion of comet surface structure and material properties. CONCERT’ s radar signals were transmitted by the orbiter and received by the lander. As the orbiter circled the comet, changing relative positions enabled measurement of comet surface parameters along different survey lines.

2.1.6 SHARAD

SHARAD (Shallow Subsurface Radar) was a payload on NASA’ s Mars Reconnaissance Orbiter (MRO) launched in 2005, primarily tasked with 探测 Mars subsurface structure and polar ice layers [8,22,25]. During its approximately 20 years of operation, SHARAD and MARSIS have essentially achieved global radar coverage of Mars.

Similar to MARSIS, SHARAD employs pulse compression mode, though with slightly different processing methods. Different processing teams use different approaches for SHARAD raw data. The Italian team uses calibration data-derived reference signals for pulse compression, then applies PGA (Phase-Gradient Autofocusing) for ionospheric correction. The U.S. team uses an equal-amplitude model for linear frequency-modulated signal frequency components, applying frequency-dependent phase error models for ionospheric correction after pulse compression. In 2019, Nerozzi et al. used SHARAD to discover extensive ice layers at approximately 1500 m depth in Mars’ north pole [8]. In 2018, the Italian Space Agency discovered a subglacial lake using MARSIS in Planum Australe, but SHARAD did not obtain similar reflected signals in this region. Comparative analysis shows MARSIS operates at 1.3-5.5 MHz, lower than SHARAD’ s 15-25 MHz. Since high-frequency components are more easily attenuated, SHARAD’ s higher operating frequency may be one reason it cannot detect reflections at the same depth.

2.1.7 LRS

LRS (Lunar Radar Sounder) was a payload on Japan’ s Kaguya orbiter launched in 2007, primarily tasked with 探测 lunar subsurface structure [9,10].

LRS employs frequency-modulated continuous wave mode with a center frequency of 5 MHz and sweep range of 2 MHz. Pulses are transmitted through a 12-meter dipole antenna array, with returned signals received by a second vertically oriented dipole array. Pulses repeat every 50 milliseconds at a scan rate of 10 MHz/s, penetrating several kilometers below the lunar surface with vertical resolution of approximately 75 meters. LRS helps study thermal histories of lunar surface regions on timescales of hundreds of millions of years and 探测 plasma waves, solar and planetary radio waves between 10 Hz and 30 MHz [10].

2.1.8 Mini-SAR

Mini-SAR (Miniature Synthetic Aperture Radar) was a payload on India' s Chandrayaan-1 mission launched in 2008, primarily tasked with 探测 whether water ice exists in permanently shadowed regions a few meters below lunar polar regions. Research suggests icy materials may exist in lunar polar locations. Mineral structures containing water droplets from comet debris and meteorites frequently impact the lunar surface. While most water evaporates in space, significant amounts accumulate over time [12].

Mini-SAR receives in both left- and right-circular polarization while transmitting in right-circular polarization. It can measure surface reflectivity, roughness, circular polarization ratio, and dielectric constant. Ice exhibits coherent backscatter opposition effect, increasing reflectivity and circular polarization ratio—changes detectable by Mini-SAR. In 2009, Chandrayaan-1 lost contact with ground stations. In 2010, NASA used Mini-SAR data to obtain images of nearly 40 craters near the lunar north pole containing water ice.

2.1.9 Mini-RF

Mini-RF (Miniature Radio Frequency) was one of seven payloads on NASA' s 2009 Lunar Reconnaissance Orbiter (LRO), primarily tasked with searching for subsurface water ice. The instrument can also capture high-resolution images of permanently shadowed regions on the Moon. Mini-RF is a synthetic aperture radar with 30-meter resolution, offering smaller size, lower power consumption, and lower cost compared with conventional space-borne synthetic aperture radar [26].

The LCROSS detector found water ice evidence in Cabeus crater, but Mini-RF did not detect water ice there. Mini-RF observations of lunar north pole craters suggest water ice may exist, though its form and quantity require further study. In 2011, Mini-RF malfunctioned and could only receive signals transmitted from Earth and reflected off the Moon.

2.2.1 MOSIR

MOSIR is a payload on China' s HX-1 orbiter planned for 2020 launch. It will obtain dual-frequency, dual-polarization radar echo data of Mars' surface and subsurface to study Mars subsurface structure and subsurface water ice. Echo data can also be used to obtain spacecraft nadir altitude for topographic studies. During Earth-Mars transfer orbit, it will conduct interplanetary very low frequency radio spectrum 探测 to obtain interplanetary VLF spectrum data.

The orbiter subsurface 探测 radar employs linear frequency-modulated pulse compression with HH and HV polarization modes. As the orbiter flies around Mars, the transmitter radiates electromagnetic signals toward the surface. Some signals reflect from the surface; others penetrate the subsurface, propagating underground and generating echoes when encountering interfaces between different media such as soil, ice layers, and rocks. Echo analysis yields information about orbiter nadir altitude, surface and subsurface layered structures, water ice signals, and total electron content (TEC) of the ionosphere. Additionally, the orbiter radar conducts very low frequency 探测 (10 kHz-10 MHz), with the subsurface radar not transmitting during VLF 探测. The radar signal processing module processes signals in two parallel bands (10 kHz-500 kHz and 500 kHz-10 MHz).

2.2.2 RIME

RIME (Radar for Icy Moons Exploration) is a payload on ESA and NASA' s planned JUICE (Jupiter Icy Moons Explorer) mission for 2022 launch. Its primary objectives are: exploring the potential habitability of Ganymede; 探测 active regions on Europa; studying Callisto' s formation in the early Jupiter system; and determining ice shell distribution and surface age [27].

After optimization analysis of radar penetration capability, reflector roughness, and Jupiter radio noise, RIME adopted a frequency of 9 MHz with 3 MHz bandwidth, transmitted by a 16-meter dipole antenna, enabling 探测 up to 9 km below Jupiter' s moon surfaces with 30-meter vertical resolution. The dielectric constant difference at ice-water interfaces is large, causing radar wave reflection. Interface information can be used to calculate losses and determine scatterer sizes within ice. Additionally, radar signal attenuation in ice is a function of composition and temperature, enabling inversion of ice layer temperature and composition from measured signals.

3. Rover Radar

Rover radar conducts in-situ 探测 of planetary surfaces using radar onboard rovers. Being closer to the surface than orbiter radar, rover radar effectively eliminates space propagation loss and complex electromagnetic background interference [6], achieving higher resolution of subsurface structures. However, due to slow rover movement, 探测 is limited to local surface areas with low efficiency. and list basic parameters of rover radars currently in service and planned for future missions.

3.1.1 SEP

SEP (Surface Electrical Properties) was a payload on the U.S. Apollo 17 mission launched in 1972, primarily used to measure dielectric constant and loss tangent and study lunar subsurface layering [28].

SEP' s transmitting antenna was a crossed dipole, with receivers consisting of three mutually perpendicular coils. The transmitting antenna was fixed on the lunar surface while receivers were mounted on the rover for dynamic measurement during movement. SEP calculated dielectric constant and loss tangent using interference between surface and subsurface waves. SEP data could also study interfaces from different underground media and subsurface structures [28,29]. SEP was the original rover radar; because its transmitting antenna was fixed on the surface, signal attenuation became significant when the rover traveled long distances, requiring antenna repositioning and resulting in low 探测 efficiency.

SEP measured ice dielectric constant of 3.3 and loss tangent of 0.1, consistent with typical values measured by other methods. Ice depth measured in field experiments (25 meters) also agreed with true values obtained by other methods. Within 1-32 MHz, depending on layer structure and electrical properties, layering could be detected from 5 meters to several kilometers. At 2 MHz, 8 MHz, and 16 MHz, large scatterers of 35-meter size showed distinct features. At 1 MHz and 2 MHz, signals from large scatterers smaller than 35 meters disappeared, making echo detection impossible [28].

3.1.2 LPR

LPR (Lunar Penetrating Radar) is a payload on China' s Chang' e-3 and Chang' e-4 rovers launched in 2013 and 2018, respectively, primarily tasked with 探测 regolith thickness and shallow structure along roving paths [30-33].

The lunar penetrating radar uses separate transmitting and receiving antennas, with the transmitting system generating microsecond electromagnetic pulses. During propagation through the lunar subsurface, electromagnetic waves are reflected and scattered when encountering inhomogeneous layers, media interfaces, lava tubes, and boulders. The receiving antenna captures echo signals, which after amplification and sampling yield 探测 data. Analysis, processing, and imaging of this data can invert regolith thickness and distribution, boulder and lava tube distribution, and lunar crust subsurface geological structure along the rover path [32].

Operating close to the lunar surface, the lunar penetrating radar effectively eliminates electromagnetic background and space attenuation effects, achieving higher resolution and signal-to-noise ratio, yielding many scientific results. Xiao Long et al. used Chang' e-3 LPR data to study lunar subsurface, identifying nine layered structures indicating complex geological activity in the region. Zhang Jinhai et al. used Chang' e-3 LPR data to determine lunar regolith thickness of about 5 meters, greater than previous estimates [34]. Zhang Jinhai et al. concluded that the thick regolith indicated surface materials near the rover path were not ejecta deposits from nearby impact craters [35]. Lai Jialong et al. calculated subsurface dielectric constants using diffraction hyperbolas in Chang' e-3 LPR profiles, identifying three subsurface layers with thicknesses of 0.95 m, 1.25 m, and 1.7 m based on dielectric constant differences [36]. Xing Shuguo analyzed LPR data to determine radar penetration depth of 136.9-165.5 m in low-frequency mode and 13-17.5 m in high-frequency mode [37]. Chang’ e-4’ s LPR achieved humanity’ s first rover radar 探测 on the lunar far side. Li Chunlai et al. used Chang’ e-4 rover radar data to delineate subsurface structure near the landing site [Figure 24: see original paper], showing: (1) Chang’ e-4’ s high-frequency radar penetration depth was much greater than Chang’ e-3’ s; (2) the lunar far side subsurface consists mainly of low-loss, high-porosity granular materials and boulders of various sizes; (3) the mare basement top should be deeper than 40 meters [38].

3.2.1 WISDOM

WISDOM (Water Ice and Subsurface Deposit Observation on Mars) is a payload on ESA’ s planned ExoMars mission’ s Rosalind Franklin rover for 2020 launch. WISDOM is a surface penetrating radar with scientific objectives to study shallow subsurface properties and search for evidence of past and present life on Mars [39].

WISDOM is an ultra-high frequency stepped-frequency radar operating at 500 MHz-3 GHz with 2.5 GHz bandwidth. It transmits numerous continuous wave signals through its antenna, each corresponding to one frequency for a step time interval. One measurement requires measuring echoes at each frequency covering the entire operating band, obtaining the real part of backscattered signals. After measurement, Hilbert transform is applied to invert the complex transfer function of the radar-covered environment, followed by inverse Fourier transform to return signals to the time domain. Different spectral window functions are applied to echoes to reduce range sidelobes, and filtering improves signal-to-noise ratio [40]. [Figure 25: see original paper] shows WISDOM field test radar profiles clearly revealing stratigraphic interfaces: Figure 25: see original paper shows a ~50 cm thick dry riverbed, while Figure 25: see original paper shows two pyroclastic rock deposition layers, with the uppermost horizontal clastic rock corresponding to a ~50 cm thick global layer.

3.2.2 MAPER

MAPER is a payload on China’ s planned HX-1 Mars mission rover for 2020 launch. MAPER has high- and low-frequency channels for 探测 shallow and deep soil thickness and ice structure respectively. During rover movement, the radar transmitter generates ultra-wideband microwave signals radiating into the Martian subsurface. When encountering soil layers, ice layers, and rocks, scattered and reflected echo signals are generated. The receiving antenna captures these echoes and transmits them to the receiver for processing. Echo analysis yields geological layering, rock, and ice information along the rover path, contributing to Mars geological evolution analysis and water ice 探测. Unlike China’ s lunar penetrating radar (LPR) high-frequency channel, MAPER’ s high-frequency channel can conduct full-polarization (HH, HV, VH, VV) 探测 for analyzing and detecting water ice, scatterer shapes, and interface shapes and roughness.

3.2.3 RIMFAX

RIMFAX (The Radar Imager for Mars’ Subsurface Experiment) is a payload on NASA’ s planned MARS 2020 mission rover for 2020 launch. RIMFAX’ s primary objectives are to image Mars subsurface structure, obtain geological features beneath the surface, and provide information about subsurface composition. RIMFAX radar profile images can reveal the history of layered rocks’ past exposure on Mars, such as impact, wind erosion, and fluvial traces [41].

RIMFAX uses an ultra-wideband bow-tie slot antenna with transmitting and receiving modes that switch during operation. RIMFAX employs gated frequency-modulated continuous wave mode with three scan bands: 150-300 MHz, 300-600 MHz, and 600-1200 MHz. It has two operating modes: shallow mode, where the system gates surface reflection signals within the receiving window; and deep subsurface mode, which removes surface reflections and other strong sources while increasing system gain and transmission power [41]. RIMFAX’ s 探测 depth is 10 meters with vertical resolution of ~30 cm [41]. [Figure 28: see original paper] shows RIMFAX radar profile measured on the Midtre Lovenbreen glacier in Svalbard, Norway in 2015, revealing two interfaces: the upper glacier with lower temperature and the lower glacier with relatively higher temperature, consistent with the cold-temperate composite structure of Midtre Lovenbreen glacier [41].

4. Summary and Outlook

Surface penetrating radar is an effective method for human space exploration, facilitating research on major scientific questions such as universe formation and evolution. Deep-space exploration will also help spawn foundational and forward-looking new disciplines and technologies, promoting scientific and technological development [1]. Radar offers strong penetration, independence from illumination, all-weather capability, and high resolution, playing important roles in lunar and deep-space exploration. Radar has a long history in lunar and deep-space exploration, with ground-based, orbiter, and rover radars achieving fruitful results. Since the 20th century, increased investment in lunar and deep-space exploration has ushered in a new peak period, with humanity exploring targets farther from Earth. As 探测 distances increase and scientific questions become more complex, requirements for lunar and deep-space exploration grow higher. To meet these requirements, traditional surface penetrating radar must be improved based on existing achievements and technologies to adapt to 探测 more distant and complex deep-space targets, advancing lunar and deep-space exploration.

4.1 Development Trends in Lunar and Deep-Space Exploration

Reviewing the application history of surface penetrating radar in lunar and deep-space exploration reveals an overall progression from near to far: from initial lunar 探测 to near-Earth planets (Venus and Mars), then to more distant bodies. Future exploration will follow this principle. For specific targets, 探测 methods have generally evolved from ground-based radar to orbiter radar, then rover radar, followed by crewed landing and sample return—this represents the future development trend.

Ground-based radar observations have been achieved for all solar system bodies. Orbiter radar 探测 has been realized for the Moon, Mars, Venus, Saturn, and Jupiter. Landing 探测 has been achieved on the Moon, Venus, Mars, and Titan. Due to its unique position, the Moon is the most frequently 探测 body and the only one visited by humans. Lunar 探测 has achieved the complete chain from ground-based to orbiter to rover radar, then to crewed landing and sample return. Future lunar 探测 will develop toward crewed landing and more refined 探测. Mars exploration has achieved ground-based radar observation, orbiter 探测, and uncrewed landing/roving, with crewed landing and sample return as the next steps. and summarize major Chinese and foreign lunar and deep-space exploration missions planned for the next decade.

4.2 Development Trends for Surface Penetrating Radar

(1) Ground-Based Radar: Long-range, wide coverage, high resolution, and multi-target tracking are future development trends [13]. To improve data transmission efficiency, larger apertures are needed. As radar apertures approach design limits, combining antennas worldwide into arrays with larger equivalent apertures becomes necessary. Designing open interfaces for antenna array networking is a future trend [1,42-44]. The U.S. will complete a 240m equivalent aperture array of over 400 12m antennas by 2020, significantly improving received signal signal-to-noise ratio.

Ground-based radar offers low cost, short construction cycles, and good flexibility, yielding fruitful results in lunar and deep-space exploration. While China’ s orbiter and rover radars are mature, China currently lacks ground-based radar for deep-space 探测. Therefore, ground-based radar system development represents a future direction for China’ s radar deep-space exploration, which will advance China’ s deep-space exploration capabilities.

(2) Orbiter Radar: Large aperture, light weight, high gain, and small volume are overall development trends [13]. Low-frequency signals offer large 探测 depth but low resolution, while high-frequency signals provide high resolution but small 探测 depth. Future orbiter radars will therefore design multi-frequency 探测 modes. Additionally, orbiter radar can conduct multi-polarization multi-angle observations combined with other methods (optical, gamma-ray) to 探测 water ice, determine layered structures, and assess surface roughness [4]. Multi-polarization 探测 will become a development trend.

(3) Rover Radar: To date, only Apollo 17’ s SEP and China’ s Chang’ e-3/4 LPR have achieved rover radar 探测 on planetary surfaces. SEP’ s transmitting antenna was fixed on the surface with receivers on the rover. Its low efficiency was gradually replaced by common-offset pulse radar. LPR uses pulse radar mode with both antennas on the rover in a common-offset configuration, offering higher efficiency and resolution than SEP. However, LPR’ s pulse radar cannot simultaneously satisfy requirements for high resolution and large 探测 depth, and its high transmission power is susceptible to ionospheric effects. Unlike lunar 探测, Mars 探测 must consider ionospheric effects, making pulse radar unsuitable for Mars environments. To eliminate ionospheric effects while improving 探测 depth and resolution, rover radar must adopt frequency-modulated signals and pulse compression processing, which will become the main 探测 mode for future rover radar. In 2020, ESA, the U.S., and China plan to launch Mars probes with rovers carrying WISDOM, RIMFAX, and MAPER radars respectively, which will use stepped-frequency continuous wave, gated frequency-modulated continuous wave, and linear frequency-modulated continuous wave modes.

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