

Inversion of Martian Subsurface Dielectric Parameters Based on Orbital Penetrating Radar and Its Application in Water Ice Detection (Postprint)

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Abstract

Mars is one of the terrestrial planets in the solar system, and studying its evolution and current state is of great significance for further understanding the formation and future evolution of Earth's environment. Exploration and research on Martian surface topography and landforms have revealed that liquid water once existed on the Martian surface; therefore, searching for water ice on Mars represents one of the important scientific objectives of Mars exploration. In Mars exploration, penetrating radar utilizes the penetration characteristics of electromagnetic waves to obtain echo time delays and signal strengths from layered interfaces, thereby inverting the dielectric constant and loss tangent of subsurface materials. The dielectric characteristic parameters of the subsurface help infer important information such as the physical properties of the medium in that layer and the presence of water ice, thereby facilitating understanding of Mars's climate and geological evolution history. This article introduces the detection principles of orbiter radar; then it introduces methods for inverting the dielectric parameters of Martian media using echo data from subsurface detection radar, along with the scientific applications and achievements of these methods in detecting Martian water ice; and finally provides an outlook on the application prospects of China's orbiter radar.

Full Text

Preamble

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Abstract

Mars is one of the terrestrial planets in the solar system, and studying its evolution and current state is of great significance for further understanding the formation of Earth's environment and future evolution. Surface topography and geomorphology investigations have demonstrated that liquid water once existed on Mars, making the search for water ice one of the key scientific objectives of Mars exploration. In Mars exploration, penetrating radar utilizes the penetration characteristics of electromagnetic waves to obtain the time delay and signal intensity of reflected signals from subsurface interfaces, enabling the inversion of dielectric constant and loss tangent of subsurface materials. The dielectric properties of subsurface layers help infer important information such as the physical characteristics of the medium and the presence of water ice, thereby revealing Mars' climate and geological evolution history. This paper introduces the detection principles of orbiter radar, summarizes methods for inverting Martian dielectric parameters using subsurface radar echo data, reviews the scientific applications and achievements of these methods in detecting Martian water ice, and provides an outlook on the application prospects of China's orbiter radar.

Keywords: Mars; dielectric constant; orbiter radar; subsurface; water ice**1 Introduction**

Mars is the planet most similar to Earth in the solar system. Exploring its subsurface structure helps us study Mars' impact history, geological modification processes, and environmental evolution, providing further insights into Earth's own evolution. Since the 1960s, humanity has implemented over 40 Mars exploration missions [?]. Surface geological surveys have confirmed that Mars once had extensive water flow [?, ?]. In 1972, images from Mariner 9 first revealed large-scale erosion features of giant channels and valley networks on Mars. Subsequently, Viking in 1975 provided more details about these channels and valleys, whose topographic features likely represent traces preserved after fluvial erosion. Liquid water is considered fundamental to life, and exploring

liquid water on Mars is crucial for searching for signs of life [?, ?]. Therefore, finding various forms of water represents a primary scientific goal for many Mars missions.

Mars' subsurface records important information about planetary formation and evolution. Detecting and studying the physical properties and structure of subsurface layers enables deeper understanding of Martian mineral resources and geological evolution history. Ground-penetrating radar (GPR) is one of the most suitable geophysical methods for planetary exploration because planetary shallow crusts are typically dry or cold, conditions that facilitate deep electromagnetic wave penetration [?]. Orbiter penetrating radar, with its high orbital altitude and coverage, enables large-scale aerial surveys, making it an effective tool for probing Martian subsurface structures and various forms of water.

The working principle of penetrating radar involves transmitting electromagnetic waves toward the planetary surface and receiving reflected and scattered waves from internal dielectric discontinuities, as well as transmitted waves that penetrate the interior. By analyzing echo characteristics such as time delay, amplitude, and frequency, combined with inversion models, planetary dielectric parameters can be inverted to detect and image internal structures. Radar technology has been widely applied in lunar, Martian, and other celestial body explorations, yielding rich scientific results and playing important roles in deep space missions [?]. This paper first introduces domestic and international orbiter radars, then summarizes their dielectric parameter inversion methods, and finally presents scientific applications and achievements in detecting liquid water and water ice on Mars, providing reference for radar data processing in China's Mars exploration missions.

2.1 Domestic and International Mars Orbiter Radars

Currently, three Mars orbiter radars are operational for subsurface detection: Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), Shallow Subsurface Radar (SHARAD), and Mars Orbiter Subsurface Investigation Radar (MOSIR). All three are synthetic aperture radars (see Figure 1 [Figure 1: see original paper]) that use different operating parameters and data processing algorithms to achieve varying detection depths and resolutions. Below we introduce them separately and compare their main parameters.

MARSIS, onboard the European Space Agency's Mars Express orbiter launched in 2003, has provided substantial data and research results for ionosphere and subsurface investigations. The instrument consists of a 40 m antenna, transmitter/receiver system, and digital electronics, being the first instrument capable of probing beneath the Martian surface (approximately 5 km). Its operating frequency band is 1.3–5.5 MHz, divided into four sub-bands of 1 MHz bandwidth each: 1.3–2.3 MHz, 2.5–3.5 MHz, 3.5–4.5 MHz, and 4.5–5.5 MHz, with a vertical resolution of 150 m in vacuum and penetration depth up to 3.7 km in ice caps. MARSIS is a non-focused SAR that uses Doppler beam sharpening (DBS) to

improve the subsurface-to-surface echo ratio [?], achieving optimal horizontal resolution of 2 km. Picardi et al. [?], Plaut et al. [?], and Holt et al. [?] introduced MARSIS-detected subsurface structures and water ice characteristics in Mars' polar regions, promoting international water ice research.

NASA's Mars Reconnaissance Orbiter (MRO), launched in 2005, carried SHARAD provided by the Italian Space Agency, the second orbiter radar operating at Mars. SHARAD operates at 15–25 MHz with 10 MHz bandwidth, offering higher range resolution (15 m in free space) compared to MARSIS, with ice cap penetration depth up to 1.7 km. SHARAD is a focused SAR using chirp scaling (CS) algorithm for data processing, achieving optimal horizontal resolution of 300 m [?]. Due to its superior vertical resolution, SHARAD's main advantage lies in mapping finer stratigraphic structures, revealing more details of polar layered deposits and adding a third dimension to observed sedimentary structures. SHARAD began scientific operations on October 3, 2006, collecting radar data from surface and subsurface. Its primary scientific objectives include mapping subsurface interfaces to depths of several hundred meters at selected sites and searching for information about subsurface ice layers, rocks, and possibly meltwater. Current data demonstrate SHARAD's capability to detect kilometers of ice-rich polar deposits [?].

China launched TianWen-1 in 2020, comprising an orbiter and rover, both equipped with subsurface penetrating radars for comprehensive orbital and in-situ exploration. The orbiter carries MOSIR [?]. Considering the optimal trade-off between penetration depth and range resolution, MOSIR operates in low and high frequency modes: 10–15 MHz, 15–20 MHz, and 30–50 MHz bands. The 5 MHz and 20 MHz bandwidths achieve 7.5 m and 30 m vertical resolution in free space, respectively, with ice cap penetration depth exceeding 1 km. MOSIR is a focused SAR currently using back projection (BP) algorithm for real-time onboard focusing [?], achieving horizontal resolution at the hundred-meter level. MOSIR's scientific objectives include: (1) observing low-frequency radio wave intensity during orbital insertion; (2) radar probing of Martian surface and subsurface structure using cross-polarized echoes; (3) measuring surface topography; and (4) measuring total electron content of the Martian ionosphere.

As the two orbiter radars with numerous results, MARSIS and SHARAD data are often analyzed jointly. Fois et al. [?] compared radar images from both systems over the same region. MARSIS detected signals from 3 km depth, while SHARAD received much weaker signals at the same depth. However, SHARAD could reveal stratification at 100–200 m depth, which MARSIS could not resolve due to lower vertical resolution. In summary, MARSIS and SHARAD provide complementary information: MARSIS probes deeper structures while SHARAD adds finer geological details of the upper crust.

Water ice detection is the primary scientific goal for all three radars. MARSIS and SHARAD have acquired extensive data over more than a decade, covering broad regions. Compared to these, MOSIR offers unique dual-frequency and dual-polarization advantages. First, its dual-frequency operation includes

a low band (10–20 MHz) between MARSIS and SHARAD frequencies, and a high band (30–50 MHz) above both. For controversial sites, such as the liquid water detected by MARSIS that SHARAD cannot confirm due to insufficient penetration of the South Polar Layered Deposit (SPLD) bottom, MOSIR’s dual-frequency capability can provide valuable complementary verification. Second, Earth-based water ice research shows radar echoes are affected by ice polarization characteristics, enabling ice detection [?]. Therefore, MOSIR’s dual-polarization capability will play an important role in Martian water ice detection. Liu et al. [?] analyzed MARSIS subsurface results at different frequencies, finding that 1–5 MHz low-frequency waves provide good penetration but low resolution, potentially causing inaccurate inversion. Frequencies of 5 MHz or lower may be more suitable for ionosphere than subsurface detection, while frequencies above 50 MHz have very shallow penetration (100 m or less, depending on dielectric properties), limiting detection range. Considering these factors, China’s orbiter radar uses 15–20 MHz center frequency, achieving high resolution while ensuring penetration depth and facilitating comparison with SHARAD data. MOSIR’s dual-frequency/dual-polarization capability fills gaps in foreign radars regarding detection depth, resolution, and polarization characteristics, complementing existing data. Building upon mature MARSIS and SHARAD data processing and inversion theories, many related methods can be directly applied to MOSIR, providing scientific foundations for Mars climate change and evolution history. Table 1 compares the main parameters of MARSIS, SHARAD, and MOSIR.

2.2 Orbiter Penetrating Radar Working Principle

Among methods for detecting Mars’ structure and properties, radar better obtains physical information such as stratigraphic structure, reflectivity, surface morphology, and dielectric constant. The radar transmits electromagnetic waves of certain frequencies that penetrate the Martian surface, analyzing reflected echoes to obtain subsurface medium information—essentially utilizing differences in physical properties for detection.

Figure 2 [Figure 2: see original paper] illustrates the detection principle for a two-layer model. Assuming the surface medium has dielectric constant ϵ_1 and the subsurface medium ϵ_2 , the orbiter radar’s electromagnetic waves travel through the atmosphere to the surface. The first echo received by the antenna comes from the nadir point A with shortest distance, with time delay $2H/c$. Part of the incident wave continues propagating downward, attenuating depending on wavelength and electromagnetic properties, then reflects at the dielectric interface producing the next echo. Generally, higher detection frequency means shorter wavelength, poorer penetration but higher range resolution for finer shallow structure; lower frequency means longer wavelength, deeper penetration but lower resolution, suitable for deep structure detection. During wave propagation from antenna to surface, amplitude and phase distort due to ionospheric effects, requiring ionospheric correction in subsequent signal processing [?, ?].

To determine whether echoes originate from subsurface interfaces rather than surface clutter from rough terrain, clutter simulation is typically performed to extract useful subsurface echoes [?].

3 Inversion Methods for Martian Dielectric Parameters

The dielectric properties of Martian surface materials are crucial parameters characterizing electromagnetic energy scattering and transmission in Martian soil. The key to understanding the interaction mechanism between propagating electromagnetic energy and subsurface materials lies in recognizing that radar images display not the actual cross-section of the 探测区域, but the time-varying response of subsurface materials recorded by the receiving antenna. We must investigate how macroscopic material effects influence radar signal attenuation and propagation velocity to extract meaningful target property information. The complex permittivity ϵ^* is commonly used to characterize Martian medium properties:

$$\epsilon^* = \epsilon_0 \epsilon_r = \epsilon_0 (\epsilon' - j\epsilon'')$$

where ϵ_0 is free space permittivity ($\epsilon_0 = 0.8854 \text{ F/m}$), ϵ_r is complex relative permittivity, ϵ' is the real part (commonly called dielectric constant), a primary macroscopic physical quantity reflecting medium polarization behavior and energy storage capability, and ϵ'' is the imaginary part related to conductivity:

$$\epsilon'' = \frac{\sigma}{\omega}$$

where σ is conductivity and ω is angular frequency. Nearly all non-metallic minerals have dielectric constants ϵ' between 4–13, while metallic minerals range 17–74 or higher. For Martian materials, mineral composition, structure, and test frequency are the main factors determining complex permittivity. δ is the dielectric loss angle, and $\tan \delta$ is the loss tangent, reflecting electromagnetic energy loss in the medium:

$$\tan \delta = \frac{\epsilon''}{\epsilon'}$$

Dielectric constant and loss tangent are important parameters for studying Martian regolith, determining electromagnetic wave penetration depth and attenuation in subsurface layers. This enables scientific insights such as more accurate subsurface structure mapping, inferring subsurface material composition and origin, exploring water ice, and estimating ice dust content.

3.1 Dielectric Constant Inversion Methods

Analyzing radar echoes to obtain dielectric properties of subsurface materials that produce reflected signals, thereby constraining or determining their composition and structure, is essentially a signal inversion problem. Numerous inversion methods have been proposed over the years [?]. By measuring or calculating parameters altered by subsurface media, such as echo time delay and power, we can obtain electromagnetic wave propagation velocity and attenuation information to invert dielectric parameters, providing basis for studying Martian geology and evolution. Time delay and intensity are two important parameters obtained from radar echoes. The most common methods utilize time delay differences between surface and subsurface echoes based on electromagnetic propagation characteristics, and analyze echo power intensity as observations to solve for subsurface physical parameters. These two methods and their applications are introduced below.

3.1.1 Time Delay Inversion Method

Based on electromagnetic wave propagation properties, the time delay difference Δt between surface and subsurface is:

$$\Delta t = \frac{2D\sqrt{\epsilon_1}}{c}$$

where c is vacuum light speed, D is thickness between layers, and ϵ_1 is interlayer dielectric constant. Using measured echo delay Δt , we can estimate ϵ_1 when layer thickness D is known, or estimate D when ϵ_1 is assumed.

Stuurman et al. [?] used SHARAD data combined with MOLA data to calculate dielectric constants in Utopia Planitia. The authors first performed clutter simulation using MOLA-derived digital elevation models to confirm that surface topography did not produce clutter confusing subsurface echoes. They then analyzed orbital data to obtain time delay Δt between surface and subsurface echoes, and used MOLA elevation data with geological constraints to estimate material thickness D overlying the reflector (i.e., subsurface interface depth). Finally, based on electromagnetic propagation characteristics (Equation 5), they performed linear regression using Δt and D to calculate ϵ_1 , obtaining a value of 2.8 ± 0.8 , consistent with dielectric properties of porous water-ice mixtures. Notably, this MOLA-based thickness method only applies to regions with exposed stratigraphy (obvious overburden) (Figure 3 [Figure 3: see original paper]), where subsurface positions can be clearly identified and surface/subsurface heights obtained directly from MOLA data to calculate layer thickness D .

Assuming known propagation velocity in the medium, echo delay can be converted to depth, making this method widely applicable for estimating layer thickness [?, ?, ?]. The method is simple and intuitive but has certain topographic requirements.

3.1.2 Echo Power Inversion Method

Time delay between surface and subsurface echoes is primary information for reconstructing subsurface stratigraphy, but echoes also contain interface reflection power information related to reflectivity, which is mainly influenced by material dielectric properties and interface roughness.

In practice, surface dielectric constant is often used to represent the surface medium's permittivity, requiring echo simulation. As described above, surface echo power relates to incident power and surface reflectivity, which depends on surface dielectric constant and roughness. For normal incidence, a simplified radar equation using Snell's law can estimate surface echo intensity. Assuming orbiter radar altitude R , surface echo peak power can be expressed as [?]:

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi R)^2} r_{0,1}$$

where P , G , λ , and $r_{0,1}$ are radar transmit power, antenna gain, wavelength, and surface reflectivity, respectively.

Grima et al. [?] decomposed SHARAD surface echo power P into coherent component P_c and incoherent component P_n : $P = P_c + P_n$, and expressed Martian surface echo power in terms of roughness coefficient s^2 and backscattering coefficient σ^0 :

$$P_c = \frac{P_t G^2 \lambda^2}{(4\pi)^2 (2R)^2} \Gamma_s$$

$$P_n = \int \frac{P_t \lambda^2}{(4\pi)^3 R^4} \frac{2s^2 G^2 \sigma^0}{A_0} ds$$

where Γ is the Fresnel reflectivity term and A_0 is surface echo amplitude. Both components contain roughness parameters, indicating Martian surface roughness affects surface echo power. To address this, Mouginot et al. [?] used the facet method [?] to model the Martian surface and corrected roughness effects through echo simulation, enabling surface dielectric constant inversion. Surface reflectivity $r_{0,1}$ can be expressed as:

$$r_{0,1} = \Gamma_s(\varepsilon) f_s(\text{rms}, \lambda)$$

where f is backscattering from surface topography. By dividing real echo power by simulated echo power:

$$\frac{P_{\text{simu}}}{P_{\text{real}}} = \frac{r_{0,1}^{\text{simu}}}{r_{0,1}^{\text{real}}} = \frac{\Gamma_s(\varepsilon_{\text{simu}})}{\Gamma_s(\varepsilon_{\text{real}})}$$

where ϵ_0 and P_{simu} are preset dielectric constant and its simulated echo power, while ϵ_{real} and P_{real} are real values. For surface interfaces, the Fresnel reflection coefficient Γ is:

$$\Gamma = \frac{n_i - n_j}{n_i + n_j}$$

where n_i and n_j are refractive indices on both sides of the interface. For surface interfaces, the media are vacuum and shallow subsurface material, with $n_i = 1$. Substituting the relationship between dielectric constant ϵ and refractive index n ($n = \sqrt{\epsilon}$) into Equation 11 and combining with Equation 10, the ratio of simulated to real surface echo power approximates:

$$\frac{P_{simu}}{P_{real}} \approx \frac{1 - \sqrt{\epsilon_{simu}}}{1 + \sqrt{\epsilon_{simu}}} \cdot \frac{1 + \sqrt{\epsilon_{real}}}{1 - \sqrt{\epsilon_{real}}}$$

The difference between the two represents deviation between preset and real dielectric constants. Within this framework, dielectric constant inversion based on echo power has attracted much attention and yielded many results. Building upon Mouginot et al. [?] who calculated only surface dielectric constants, many studies established two-layer models (Figure 2). For example, Liu et al. [?] developed a rough-surface two-layer geological model and derived inversion methods for surface/subsurface dielectric constants and regolith thickness based on numerical simulation and Huygens' principle. However, this method approximates steep slopes or crater edges as rough surfaces with zero mean slope, requiring relatively flat terrain for inversion.

Orosei et al. [?] identified liquid water beneath the south polar ice cap based on anomalously high subsurface echo intensity. This required assuming electromagnetic properties of Martian surface materials and establishing relationships between surface/subsurface echo power ratios and surface dielectric constants to discriminate subsurface material types. The study used known dielectric parameters of Martian materials as prior information (Table 2). For regions with obvious layered topography, time delay and echo power methods can be combined to obtain dielectric constants of first and second layers [?], where the second layer's dielectric constant is derived from power differences between signals that have or haven't passed through the first layer.

Beyond two-layer models, multi-layer inversion methods have been developed based on regional geological characteristics. Meng et al. [?] found that MARSIS and SHARAD produced different dielectric constant values for the same region in Elysium-Utopia, prompting a three-layer model analysis. Current multi-layer methods mainly study polar layered deposits, assuming each layer is smooth. Figure 4 [Figure 4: see original paper] shows a multi-layer horizontal model, where echo power P_n from the n th layer's upper surface approximates [?]:

$$P_n = P_0 r_n [(1 - r_m)^2 \exp(-k_0 c \Delta t_m \tan \delta_m)]$$

where P_0 is incident surface power, k_0 is free-space wavenumber, and r is reflectivity. Each layer's loss tangent and surface dielectric constant real part can be obtained using above methods, while other layers' dielectric constants can be derived from upper layers. Lalich et al. [?, ?] used multi-layer reflection models to invert layered dust fractions in polar deposits but could not constrain layer thickness and dust fraction. While echo power methods are more widely applicable than time delay methods (not requiring special topography), they depend on geological assumptions.

3.2 Loss Tangent Inversion Method

Surface medium loss tangent inversion assumes identical reflectivity at upper and lower surfaces. Based on Orosei et al. [?] definitions of surface and subsurface echo powers:

$$P_s = \frac{P_t \lambda^2 R_s G}{8\pi H}$$

$$P_{ss} = \frac{P_t G \lambda^2}{8\pi(H+z)} (T_s)^2 R_{ss} \exp(-2\pi f \tan \delta \Delta t)$$

where z is medium thickness, T is surface transmission coefficient, f is radar frequency, R and R_s are Fresnel reflection coefficients for surface and subsurface, and $\tan \delta$ is interlayer loss tangent. The geometric loss term represents propagation losses, while the exponential term represents attenuation from medium losses. From Equations 14 and 15:

$$\ln P_{ss}(\Delta t) = -2\pi f \tan \delta \Delta t + \ln P_s + \ln \frac{G \lambda^2}{8\pi H}$$

Thus, $\tan \delta$ has a linear relationship with $\ln P_{ss}(\Delta t)$. Fitting echo delay versus subsurface echo intensity yields a curve whose slope represents the medium's loss tangent.

In summary, theoretical foundations for inverting Martian dielectric parameters from radar data are mature, with similar practical applications but limited by lack of prior knowledge such as layer thickness and subsurface composition. More accurate acquisition of these prior values is crucial for obtaining realistic inversion results.

4 Current Status of Martian Water Ice Detection

Understanding water's role in Mars' evolution is essential for comprehending its climate, geological history, and potential habitability. Mars' polar regions are covered with finely layered deposits recording climate changes over unknown timescales, first identified in orbital images from Mariner and Viking spacecraft that revealed intersecting riverbeds, canyons, and channels—considered evidence of past liquid water. Mars exploration data have confirmed substantial water ice at both poles [?]. Today, most Martian ice resides in polar regions covering millions of square kilometers with thicknesses of kilometers. These deposits comprise geological units of different origins, compositions, and ages, recording Mars climate changes over 10^5 – 10^9 year timescales [?]. Mars' orbital obliquity variations affect water ice distribution, with ice also detected at low latitudes like the equator [?]. MOLA topography shows North Polar Layered Deposits (NPLD) and South Polar Layered Deposits (SPLD) have similar morphology and thickness [?], both roughly circular with ~1000 km diameter and maximum relief of ~3.5 km relative to surroundings. MOLA-based volume estimates suggest they represent a global layer 16–22 m thick. Orbital images show PLD consists of layers with different reflectivities, attributed to varying ice-dust mixtures. Ice-dust mixing ratios cannot be precisely measured from optical data, but just 6–10% dust can reduce pure ice reflectivity to observable levels [?]. Most polar deposit studies use radar methods, similar to terrestrial ice sheet research. MARSIS and SHARAD have conducted extensive scientific surveys of subsurface water ice and liquid water, with researchers performing comprehensive analyses yielding significant results. This section presents potential water ice regions in polar and non-polar areas.

4.1 Martian North Polar Region Water Ice Detection

The North Polar Planum (PB) consists mainly of the Northern Residual Ice Cap (NRIC), NPLD composed of water ice and dust, and Basal Unit (BU). MARSIS and SHARAD results reveal subsurface and basal structures, detecting frozen deposits in NPLD. Further analysis can estimate water ice dust content, dielectric constant, and thickness distribution. Selvans et al. [?] used MARSIS data to invert the ice-rich North Polar Planum interior. Using time delay method at bright subsurface reflection locations and assuming $n = 3$, they converted time delays to thicknesses, estimating North Polar Planum water ice volume as $(1.3 \pm 0.2) \times 10^6 \text{ km}^3$. The two components, NPLD and BU, were more precisely quantified as $(7.8 \pm 1.2) \times 10^5 \text{ km}^3$ and $(4.5 \pm 1.0) \times 10^5 \text{ km}^3$, respectively.

Picardi et al. [?] generated MARSIS radar images along nadir tracks. When MARSIS ground tracks entered NPLD regions from northern plains, reflected echoes split into two signals of comparable intensity (Figure 5 [Figure 5: see original paper]), with maximum time delay to the second reflection of 21 s. After clutter simulation confirmed the second signal originated from subsurface, the authors assumed the overburden was pure ice ($n = 3$) and used time delay method to convert subsurface delay to depth, estimating 1.8 km thick water ice.

The subsurface echo intensity was nearly as strong as the surface echo, indicating very low propagation loss between interfaces, increasing the likelihood of pure water ice. The two-layer reflection power ratio of ~ 10 dB at 5 MHz indicated low loss tangent and conductivity, suggesting pure water ice with impurity content below 2%. This contradicts melt zones at NPLD base. SHARAD's design enables higher-resolution subsurface structure detection. Phillips et al. [?] used SHARAD data to analyze NPLD internal stratification. Radar images (Figure 6 [Figure 6: see original paper]) clearly show reflections from laterally continuous layers, comprising four reflection groups separated by near-pure ice materials, plus detection of the deposit's basal unit. NPLD edge exposures confirm no basal unit beneath Gemina Lingula, where NPLD directly overlies Vastitas Borealis Formation (VBF).

Lithospheric flexural response to polar cap loading constrains cap composition and current thermal state. Selvens et al. [?] and Phillips et al. [?] used MARSIS and SHARAD data, respectively, assuming NPLD $\nu = 3$, finding no obvious lithospheric flexure beneath North Polar Planum, indicating a thick elastic lithosphere existed before BU formation. However, NPLD composition and volume largely determine flexure presence—in other words, assumed NPLD dielectric constants affect lithospheric flexure inversion results. Broquet et al. [?] combined radar data with flexural loading models and time delay method, estimating North Polar cap $\nu = 2.75$ (+0.40, -0.35). The derived cap volume would be 30% higher than current predictions, with up to 400 m lithospheric flexure beneath the cap center. When dust content exceeds 6% by volume, the composition includes 10% dry ice by volume. Broquet et al. [?] applied similar methods to South Polar cap, estimating SPLD $\nu = 2.5$ –3.4, inferring $\sim 9\%$ dust volume if dry ice is negligible, and up to 700 m lithospheric flexure.

4.2 Martian South Polar Region Water Ice Detection

South Polar Planum, similar to its northern counterpart, comprises three units: South Residual Ice Cap, SPLD, and Dorsa Argentea Formation (DAF). Plaut et al. [?] presented MARSIS SPLD results clearly showing internal stratification and strong subsurface reflections suggesting low-loss water ice. Figure 7 [Figure 7: see original paper] shows that when the detector crossed the layered deposit edge (left white arrow in Figure 7a), the echo track split into two signals of comparable intensity, with the upper surface track matching MOLA topography. Assuming the overburden is water ice, substituting water ice into Equation (5) converts the bright lower track's time delay to depth, representing an extension of surrounding SPLD surface topography. The geological structure consists of an ice-rich SPLD material overlying a debris-rich substrate, with the split lower interface representing their boundary. Assuming SPLD material is dirty water ice over basaltic basement, its loss tangent is 0.001–0.005, equivalent to 0–10% dust content. Plaut et al. [?] also generated SPLD thickness maps by subtracting interpolated basal topography from high-resolution MOLA surface topography, estimating volume as $(1.6 \pm 0.2) \times 10^6$ km³—similar to Smith et

al. [?] estimates using only MOLA data.

MARSIS' comprehensive SPLD surveys enabled Plaut et al. [?] to use MOLA surface elevations minus interpolated MARSIS basal elevations to derive SPLD thickness and distribution (Figure 8 [Figure 8: see original paper]). Khuller and Plaut [?] used MARSIS data from 2005–present to generate 3D radar image volumes. Figure 9 [Figure 9: see original paper] shows depth conversion assuming pure water ice ($\rho = 3.1$), re-estimating SPLD volume as $\sim 1.6 \times 10^6 \text{ km}^3$, consistent with Plaut et al. [?].

Polar ice-rich layered deposits contain Mars' climate history. Seu et al. [?] used SHARAD data to study Prometheus Lingula in South Polar Planum, resolving possible meter-scale subsurface interfaces. Assuming water ice $\rho = 3.5$, converted depths were 130–420 m, 340–450 m, 450–570 m, and 890–1030 m. Milkovich et al. [?] also examined Prometheus Lingula stratigraphy, finding numerous non-horizontal layers dipping toward the deposit center, indicating significant erosion during SPLD evolution. Farrell et al. [?] identified large-scale (~ 100 m) internal layering, with Prometheus basin floor extending smoothly beneath SPLD forming the basal interface, and a ~ 500 m deep interface possibly representing the ice-rich layer/basal unit boundary—suggesting possible ice-rich layers at 500 m depth.

Water's importance for astrobiology makes assessing current Martian liquid water content and state a key exploration driver. Due to low temperature and pressure, liquid water is rare on Mars, existing only briefly at the surface. However, geological and mineralogical evidence indicates past surface liquid water flow [?, ?], suggesting dramatically different ancient climates. Debate continues about liquid water beneath South Polar ice cap. Geological evidence for recent ($< \text{few million years}$) surface liquid water was first reported by Malin and Edgett [?]. Orbital radar detected an anomalously bright ~ 20 km diameter, 1.5 km deep reflector beneath South Polar ice cap [?]. Using echo power method, they established relationships between normalized subsurface echo intensity and dielectric constant, quantitatively analyzing the anomaly's relative permittivity and matching it to water-bearing materials, hypothesizing a liquid water lake stabilized by perchlorates (Mg, Ca, Na) at low temperatures. This reignited scientific debate about stable polar liquid water. Lauro et al. [?] applied terrestrial glacial groundwater detection methods, confirming the lake and inferring sporadic liquid water in SPLD basal unit. However, theoretical difficulties exist reconciling liquid water with known SPLD features [?], requiring anomalously high geothermal flux for stability. Whether the Ultima Scopuli bright reflection truly indicates liquid water requires further investigation. Smith et al. [?] alternatively proposed hydrated and clay-rich deposits as the cause. Khuller and Plaut [?] noted the bright reflection extends near the surface where annual temperatures are too low even for supercooled perchlorates, suggesting it may not be liquid water. Their improved basal topography map can serve as hydrogeological models for water potential estimates. Bierson et al. [?] argued conductivity differences, rather than dielectric constant differences, could ex-

plain high basal reflectivity, considering high-conductivity materials like clays, metal-bearing minerals, or salty ice.

In summary, MARSIS' anomalous bright basal reflection in Ultima Scopuli was initially interpreted as liquid water but has been questioned, with alternative explanations including clays, hydrated salts, and salty ice. Debate continues: Mattei et al. [?] combined simulations with new laboratory measurements showing these materials wouldn't produce strong basal reflections at MARSIS frequencies and Martian temperatures, suggesting perchlorate and oxide brines instead. Lalach et al. [?] modeled different SPLD basal compositions, demonstrating that signal interference from SPLD multi-layer structure could produce similar strong basal reflections without liquid water. Regardless, these results indicate a complex hydrological system may exist at the South Pole.

4.3 Martian Equatorial Region Water Ice Detection

Watters et al. [?] used MARSIS data to study Medusae Fossae Formation (MFF) near 140°–240°E equatorial region, obtaining deposit thickness and dielectric properties. MARSIS detected subsurface interfaces, and analyzing surface/subsurface echo delays yielded $\epsilon' = 2.9 \pm 0.4$ and attenuation coefficient (0.0048 ± 0.0024) dB/m, estimating $\tan \delta = 0.002$ – 0.006 . These parameters suggest MFF deposits are either low-density, low-loss dry materials or ice-rich materials mixed with high- ϵ' , high- $\tan \delta$ non-ice components. If the latter, substantial water ice exists beneath equatorial dust/sand layers, with volume comparable to NPLD and 10% higher dust content [?]. However, data cannot exclude the possibility of dry, porous materials. Orosei et al. [?] compared MFF dielectric properties with volcanic rocks and ice-dust mixtures, supporting high-porosity pyroclastic deposits in Lucus Planum's eastern Apollinaris Patera region. Morgan et al. [?] used SHARAD data for 3D visualization of Elysium Planitia, the youngest volcanic region, showing overlapping lava flows from multiple sources, possibly from MFF materials. These deposits show unique characteristics compared to other Martian sediments detected by radar.

4.4 Martian Mid-Latitude Region Water Ice Detection

Mars' orbital and obliquity variations determine stable water ice locations. Current climate and obliquity combined with water ice stability models indicate stable subsurface ice at mid-latitudes [?]. Bramson et al. [?] studied Arcadia Planitia at mid-latitudes using crater terrace depths and SHARAD profiles. Time delay method with depth and radar delay estimated dielectric constants, inferring a 10 m thick layer between surface and subsurface is primarily water ice, representing $\sim 10^4$ km³ of excess ice.

Utopia Planitia, the largest impact basin (3300 km diameter) in Mars' northern mid-latitudes, contains polygonal and fan-shaped depressions. Morphological analysis shows subsurface reflectors correlate with layered terraces in southwestern Utopia Planitia. Degradation features like fan-shaped depressions and

basal exposures are common. Studies describe these terraces as young, dark-toned terrain with abundant periglacial morphology, primarily volcanic ash deposits whose pore space became ice-rich after atmospheric deposition and brief thawing [?], indicating substantial near-surface water ice. Mars' climate evolution history also favors subsurface ice accumulation in northern mid-latitudes [?]. Combined with radar observations, Utopia Planitia is inferred to be water ice-rich. Stuurman et al. [?] verified this using SHARAD data, identifying a 375,000 km² radar detection area in southwestern Utopia Planitia with typical time delay method topography. They estimated overburden material $\tau = 2.8$, consistent with water ice, air, and rocky material mixtures. Composition analysis indicated <30% rocky debris, 50–85% water ice, and 15–50% pore space, with water ice volume up to 14,300 km³. Figure 10 [Figure 10: see original paper] shows Utopia Planitia outline (black line) and southwestern study area (striped). Figure 11 [Figure 11: see original paper] presents subsurface detection results: A.i and A.ii show SHARAD track 1346901 data and clutter simulation, with white arrows indicating subsurface positions, yellow lines showing MOLA topography, and A.iii showing MOLA color elevation with subsurface interface locations (black dots) and radar track (white line). B.i–B.iii show track 1389101 similarly. Subsurface interface locations correlate with topographic elevation, occurring mainly on terraces.

Lobate debris aprons (LDA) distributed at 30°–60° latitudes in both hemispheres contain water ice, indicating ice presence at mid-low latitudes. Plaut et al. [?] analyzed LDAs in Deuteronilus Mensae (northern mid-latitudes) using SHARAD data, finding they are primarily water ice. When SHARAD crossed these features, radar echoes split into two reflections. MOLA elevation modeling and clutter simulation confirmed the second echo was subsurface, not off-nadir surface clutter. Strong reflections from LDA tops and bottoms indicate predominantly pure water ice between them, evidence that LDAs in Hellas Planitia are glaciers covered by thin rock layers. Time delay method estimated LDA $\tau = 3$ with attenuation ~ 2 dB/s, consistent with pure or mixed water ice. SHARAD also discovered buried glaciers in southern mid-latitudes [?]. Radar images show LDAs in three craters in eastern Hellas Planitia are actually glaciers buried beneath dust and rock layers. Scientists believe snow and ice accumulated at higher elevations, flowed downward, and are now protected from sublimation by debris cover, with surface grooves and ridges caused by deforming ice. These may represent the most extensive non-polar ice discovered on Mars. Holt et al. [?] indicate these deposits contain substantial water ice from high-obliquity periods, now hidden beneath a thin protective layer with dust content <10%. Surface morphology estimates suggest LDAs in eastern Hellas Planitia alone may contain $\sim 28,000$ km³ of water ice. Karlsson et al. [?] estimated total LDA water ice volume in four mid-latitude regions (Figure 12 [Figure 12: see original paper]), two each in northern and southern hemispheres (regions 1, 2 and 3, 4, with 3 and 4 in eastern Hellas Planitia). Using ice flow models, MOLA elevation, and SHARAD data, they inverted LDA ice thickness and yield stress, solving area-volume relationships to estimate current Martian LDA total water

ice volume as $1.55 \times 10^5 \text{ km}^3$ ($\pm 25\%$), equivalent to a global 1.1 m ice layer. The area-volume relationship resembles terrestrial ice sheets and ice caps more than valley glaciers, suggesting LDAs are flatter and more ice-cap-like.

Table 3 lists Martian water ice detection regions and their ice composition/volume, showing SPLD generally has higher dust content than NPLD.

5 Summary and Outlook

Exploring Mars' subsurface is crucial for finding life, as subsurface water is considered one of the most likely water forms on Mars. Detecting groundwater remains a primary exploration objective. Radar payloads, utilizing electromagnetic wave propagation, are the only instruments capable of revealing subsurface structure, playing significant roles in Mars topography, subsurface material, and structure exploration, providing scientific basis for studying climate and geological evolution, with important prospects for water ice detection.

Europe and the US have acquired extensive macroscopic data of Mars' surface, subsurface, and ionosphere using SHARAD and MARSIS. Numerous inversion methods for Martian subsurface dielectric parameters have been proposed. Time delay and echo power methods play important roles in analyzing subsurface dielectric properties, each with advantages and applicable conditions, both requiring prior geological knowledge (e.g., layer thickness, composition). Polar regions often assume water ice dielectric constants for thickness estimation, while other regions combine local geological conditions and history to validate assumptions. Echo power methods require comparing real and simulated values with geological context to derive appropriate dielectric constants. Therefore, developing better radar echo interpretation methods requires additional geological constraints (layer thickness, composition, dust content) from other detection methods to improve interpretation accuracy.

Building upon rich international results, China's first Mars exploration mission is highly innovative and challenging. Based on existing methods, we recommend for MOSIR data processing:

1. Forward radar echo simulation, widely used in lunar rover radars [?, ?], can be applied to high-precision Martian surface modeling and echo simulation. MOSIR's dual-polarization capability requires considering different polarization scattering patterns in simulations to better match actual data.
2. Use simulated echoes to calculate polarization characteristics such as circular polarization ratio and polarization degree, summarizing features under specific layered structures to validate polarization extraction methods, providing reliable criteria for dielectric parameter inversion and polarization analysis of real data.
3. Integrate multi-source Mars radar data, conducting comprehensive analysis of MARSIS, SHARAD, MOSIR, and China's rover-mounted subsurface

penetrating radar (RoSPR) data. This supplements and validates detection data at different depths and resolutions, yielding more reliable global Martian “water resource” distribution characteristics.

With advancing aerospace technology and improving deep space exploration precision, China has begun Mars exploration research. Radar detection of Martian water ice and liquid water remains a hot scientific topic. We must fully utilize international data, summarize previous experience, and maximize TianWen-1’s polarimetric radar advantages.

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