Radar Sounding and Research Status of Mars Subsurface: Postprint

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

Abstract

Extensive studies of Martian geomorphology and surface material composition have indicated that surface water once existed on Mars, while currently detected water on Mars is extensively present in polar ice caps and the subsurface. Over the past twelve years, the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) onboard ESA' s Mars Express and the Shallow Radar (SHARAD) onboard NASA' s Mars Reconnaissance Orbiter have conducted subsurface exploration and research on Mars, achieving a series of scientific results. The Martian subsurface records important historical information concerning the planet' s formation and evolution. Exploration and study of the Martian subsurface can provide scientific evidence for understanding Mars' physical properties and structural composition, searching for life on Mars, and investigating its geological evolution history. This paper reviews current radar-based exploration and research of the Martian subsurface, introduces the principles and methods of radar sounding, summarizes the scientific results achieved, and prospects future Mars exploration radars.

Full Text

Radar Detection and Research Status of Mars Subsurface

Abstract

Extensive studies of Martian geomorphology and surface material composition indicate that liquid water once existed on the Martian surface, while currently detected water on Mars is widely present in polar ice caps and the subsurface. Over the past twelve years, the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) onboard ESA' s Mars Express and the Shallow Subsurface Radar (SHARAD) onboard NASA' s Mars Reconnaissance Orbiter have conducted subsurface exploration of Mars, achieving a series of scientific results. The Martian subsurface records important historical information about the formation and evolution of Mars. Probing and studying the Martian subsurface provides scientific evidence for understanding the physical properties and structural composition of Mars, searching for Martian life, and studying its geological evolution history. This paper reviews current radar-based exploration and research of the Martian subsurface, introduces the principles and methods of radar detection, summarizes the scientific achievements obtained, and looks ahead to future Mars exploration radars.

Keywords: Mars; Subsurface; Water ice; MARSIS; SHARAD

1. Introduction

Mars is the fourth planet from the Sun and one of the four terrestrial planets in the solar system [1]. Numerous studies of Martian geomorphology and surface material composition suggest that liquid water once existed on the Martian surface. Currently detected water on Mars is widely distributed in polar ice caps and the subsurface. The Martian subsurface, defined as the region below the surface crust, records important historical information about the formation and evolution of Mars. Studying the Martian subsurface can provide scientific evidence for understanding the planet’ s physical properties and structural composition, searching for life, and investigating its geological evolution history.

Since Galileo first observed Mars with a telescope, astronomers have used optical telescopes for over a century to obtain extensive knowledge about Martian surface features. In 1963, humans first used ground-based radar to obtain echoes from the Martian surface, a technique that has been employed during most Mars oppositions [2]. This radar method can provide information about physical properties such as surface roughness and dielectric constant [3]. To date, humans have conducted numerous Mars exploration missions, with spacecraft investigating Martian surface morphology and various detection technologies being applied. Radar sounders play a unique role in Mars exploration because the electromagnetic waves they emit can penetrate the Martian surface to probe subsurface structures from several meters to several kilometers deep [5]. This capability offers significant advantages for understanding the geological stratification of the upper crust, the presence and distribution of water on Mars, and provides scientific evidence for studying Martian geological evolution history and searching for life.

Radar detection technology has been widely applied in lunar and other planetary exploration, yielding rich scientific results. The radars currently used for Mars subsurface detection include MARSIS onboard ESA’ s Mars Express, launched in 2003, and SHARAD onboard NASA’ s Mars Reconnaissance Orbiter (MRO), launched in 2005. China’ s first Mars exploration mission was formally approved in 2016, with a Mars probe (including an orbiter and a rover) scheduled for launch in 2020, each carrying a Mars subsurface detection radar. Therefore, understanding the principles of Mars radar detection, scientific objectives, and current research status is particularly important.

2. Mars Subsurface Structure

2.1 Subsurface Structure Models Martian surface morphology indicates that liquid water likely flowed on Mars in the past [7]. However, due to the current thin Martian atmosphere (approximately 6 hPa) and low surface temperatures (around 210 K), liquid water cannot stably exist on the surface. The Mars Orbiter Camera (MOC) onboard Mars Global Surveyor revealed possible water in shallow subsurface structures several hundred meters deep, likely sourced from subsurface ice layers covered by volcanic alteration products [8].

Impact processes from meteorites and small celestial bodies have played important roles in the structural evolution of the Martian crust, generating and distributing large amounts of ejecta. Throughout Martian geological history, impact ejecta could cover the entire Martian surface. An idealized physical profile of the Martian crust consists of: an upper layer of regolith composed of fragmented ejecta, weathered materials, and sediments; a middle layer of fractured bedrock formed by geological processes such as impact cratering; and at certain depths, overlying pressure becomes sufficient to cause self-compaction of materials. It has been predicted that at depths of about 2.5 km, temperature gradients may reach the melting point of ice, and fractured subsurface ice layers could potentially harbor liquid water [9].

A more detailed hypothetical model of Martian subsurface structure divides it into shallow and deep subsurface layers based on conductivity. From the surface to 400 m depth is the shallow subsurface, primarily composed of fragmented volcanic alteration products, weathered materials, and sediments, which are lossy media for radar waves. The region from 400 m to 2.5 km depth is the deep subsurface, consisting of a frozen layer of subsurface ice and fractured porous volcanic rock, with ice or liquid water filling pores and fractures. Compared with the shallow subsurface, the deep subsurface absorbs less radar energy, and its electrical properties depend on the thermodynamic stability of ice, which in turn depends on ice salinity, geothermal gradient, and rock porosity. Liquid water may exist at depths of about 2.5 km [10].

The polar regions have very different subsurface structures. Like Earth' s polar regions, Mars' polar areas are covered by extensive, kilometer-thick water ice deposits that record climate change history. The Martian north polar region (Planum Boreum, PB) consists of the Northern Residual Ice Cap (NRIC), North Polar Layered Deposits (NPLD), and Basal Unit (BU) [11]. The south polar region (Planum Australe, PA) comprises the Southern Residual Ice Cap (SRIC), South Polar Layered Deposits (SPLD), and Dorsa Argentea Formation (DAF). Each polar ice cap consists of seasonal ice caps and permanent residual ice caps. High-resolution images show that the NRIC has uniformly distributed pits at 10-20 m scales, with pit bottom colors matching the underlying NPLD, indicating the NRIC thickness equals pit depth. The SRIC consists of high-albedo solid

CO_2 ice several meters thick [11].

3. Principles of Orbital Penetrating Radar

Electromagnetic waves can penetrate soils, particularly dry soils with low conductivity, as well as rock and ice layers. Orbital penetrating radar utilizes this capability to probe the upper crustal structure of terrestrial planets. The radar transmits electromagnetic waves toward the Martian surface; part of the energy is reflected at the surface and received by the radar, while another portion propagates below the surface. The attenuation depends on wavelength and medium properties such as conductivity and permeability. At interfaces where dielectric constants differ, electromagnetic waves undergo reflection and transmission again, enabling the radar to distinguish different geological layers such as sedimentary and bedrock layers, or water-ice-bearing porous rocks versus dry porous rocks.

From radar detection data, subsurface depth can be used to study lithospheric properties, Martian climate, and geological evolution processes. The two most important parameters obtained from inversion are subsurface depth and the dielectric constant of each layer' s material, which can indicate physical properties and the presence of water ice.

shows the main parameters of MARSIS and SHARAD [14-16].

4. MARSIS and SHARAD Instruments

MARSIS is a multi-band low-frequency synthetic aperture radar on Mars Express, primarily for detecting water distribution from the surface to 5 km depth. It was the first instrument capable of probing below the Martian surface. Its low-frequency radio waves partially reflect at the surface with most energy penetrating downward, reflecting at material interfaces. From the time delay between echoes, layer depths can be determined, and from echo strength, physical properties like dielectric constant can be inverted to reveal water content and distribution. MARSIS has high relative bandwidth (1 MHz), achieving 150 m vertical resolution in vacuum (50-100 m in subsurface). It operates at 1.8, 3, 4, and 5 MHz carrier frequencies, but only at 3, 4, and 5 MHz on the nightside due to ionospheric plasma frequency cutoff [14].

SHARAD on MRO began operations in November 2006, collecting surface and subsurface data. It can penetrate about 1 km, with primary science objectives of detecting global subsurface ice layers, possible liquid water, and polar ice cap structure. Its center frequency is 20 MHz with 10 MHz bandwidth, enabling 15 m vertical resolution in vacuum (10-20 m in subsurface), allowing operation on both day and night sides [15].

Both instruments use synthetic aperture principles. MARSIS has best along-track resolution of 5-10 km × 10-30 km, while SHARAD' s focused processing improves horizontal resolution to 0.3-1 km × 3-6 km. MARSIS better penetrates to 200-3700 m depth, while SHARAD provides higher vertical resolution for 20-2700 m depth, making their data complementary [16].

5. Polar Water Ice Detection

5.1 North Polar Region MARSIS data have delineated the basal layer of Planum Boreum, detecting frozen deposits in the NPLD. The water ice volume in NPLD can be estimated, formed during a climate epoch very different from present Mars [16]. Analysis of MARSIS 3-5 MHz data shows two strong reflections when crossing the NPLD margin at 10°-30°E, with time delays of 800-900 km relative to surface echoes. High-fidelity models based on Mars Orbiter Laser Altimeter (MOLA) topography confirm these are subsurface interface reflections, not surface topography effects. The lower interface' s time delay and relative strength suggest overlying material similar to pure water ice in dielectric constant and loss tangent. Assuming pure water ice (dielectric constant 3.15), depth conversion shows the subsurface reflector is approximately co-planar with the northern plains, indicating a thick elastic lithosphere and low crust-mantle temperature gradient [17].

SHARAD data reveal internal layering in NPLD, showing continuous depositional layers separated by near-pure ice intervals. Observed basal flexure under ice load suggests current elastic lithosphere thickness >300 km, possibly requiring a transitional state controlled by mantle viscosity. SHARAD data have produced detailed subsurface structure maps, revealing many new features and showing the NPLD base is very flat and co-planar with the surrounding Vastitas Borealis plain. Inversion of MARSIS data precisely estimates water ice volumes in Planum Boreum, NPLD, and BU as (7.8$±1.3)×10^{5}$ km^3, (1.3$±0.2)×10^{6}$ km^3, and (4.5$±1.0)×10^{5}$ km^3 respectively [18].

5.2 South Polar Region Similar to the north, the south polar region has water-ice-rich deposits covering the entire area, consisting of three main units: SRIC, SPLD, and DAF. MARSIS conducted comprehensive studies of SPLD, determining its maximum thickness as 3.7$±0.4*km.AssumingSPLDcompositionisnear−purewaterice,itcontains*(1.6±0.2)×10^{6}$ km^3 of water, equivalent to an 11$±$1.4 m global water layer [19].

MARSIS detected typical SPLD internal structure [Figure 8: see original paper], showing two continuous interface echoes when crossing SPLD margins. The stronger subsurface echo indicates the ice-rich SPLD, while the lower interface represents the contact with underlying bedrock. The lack of regional down-warping and relatively flat bedrock interface reflect a very thick southern hemisphere lithosphere. Outside SPLD margins at ~150 km distance, subsurface interfaces at 600-900 m depth suggest water-ice-bearing layers [20].

SHARAD' s higher resolution enables study of SPLD internal layering. Data from Prometheus Lingula region show internal stratigraphy with layers dipping from center to margins, indicating multiple erosion events in SPLD evolution history [21]. Combined MARSIS, gravity, and MOLA data yield SPLD density of ~1,220 kg/m^3, confirming relatively pure water ice composition and revising estimates of Martian surface water inventory [22].

6. Other Regional Subsurface Studies

6.1 Athabasca Valles Located in central Elysium Planitia (5°N, 150°E), Athabasca Valles shows fragmented raft-like terrain with two formation hypotheses: volcanic lava flow crystallization or water flow origin [31]. MARSIS 5 MHz data analysis using finite-difference time-domain modeling of different geoelectric models (50 cm surface layer, frozen ocean/mudflow/basalt middle layer, basalt basement) suggests the shallow subsurface is more consistent with volcanic materials, supporting the volcanic hypothesis [32].

6.2 Medusae Fossae Formation MARSIS data reveal Medusae Fossae Formation (MFF) deposit thickness and dielectric properties. The surface-subsurface echo time delay indicates dielectric constant real part of 2.9$±$0.4, consistent with lowland plain deposits but not excluding low-density, water-poor materials. The dielectric loss suggests significant water ice presence, though with higher dust content than polar deposits [23]. SHARAD data show MFF’ s upper few hundred meters have high porosity, possibly consisting of low-density welded or interlocked pyroclastic deposits that can maintain steep ridges. Some MFF eastern regions show complete disappearance of surface echoes, likely due to high surface roughness and low near-surface dielectric constant [24].

6.3 Cerberus Palus Detailed SHARAD data analysis of Cerberus Palus (144.5°E-152.5°E, 1°N-8.9°N) shows clear surface and subsurface interfaces between Cerberus Palus (CP) and Zephyria Planum (ZP). Inverted dielectric constants suggest subsurface composition of water ice and rock. The relative dielectric constant of water ice is ~3.1, while rocks range 6-10. The main factor affecting dry rock dielectric constant is porosity, with iron oxide content also important but difficult to quantify quantitatively [25].

6.4 Apollinaris Mons SHARAD data analysis of Apollinaris Mons’ fan deposit structure (174.4°E, 9.3°S) shows multiple subsurface interfaces in the thinnest portions, indicating complex internal stratification. The estimated dielectric constant real part is 3.6-4.0, consistent with volcanic mudflow or pyroclastic flow origins [26].

6.5 Buried Basins in Northern Lowlands MARSIS data revealed large impact basins buried beneath flat terrain in northern lowlands. While previous studies suggested younger northern crust, MARSIS detection of >200 km diameter basins indicates northern crust is at least as old as exposed southern highland crust, proving the Martian crustal dichotomy formed early in geological history [27].

6.6 Mid-Latitude Buried Glaciers SHARAD data discovered buried glaciers in southern mid-latitudes. Radar sounding of lobate debris aprons near Hellas impact crater rim shows subsurface echoes inconsistent with surface echoes, confirmed in adjacent orbits. After depth conversion assuming water-ice composition, the low attenuation similar to polar layered deposits indicates water ice presence within the aprons, suggesting ancient glaciers buried by rock debris [28].

7. Global Dielectric Constant Inversion and Water Distribution

Using MARSIS 3-5 MHz data, the first global map of Martian surface dielectric constant was produced. Surface echo strength variations primarily reflect kilometer-scale surface roughness. Normalizing with MOLA topography-derived MARSIS simulations yields shallow dielectric constant maps [29]. The dielectric constant varies with latitude: high values in mid-latitudes (20-40°), low values in equatorial and high-latitude regions. Comparison with Gamma Ray Spectrometer (GRS) neutron data [43-44] shows that decreasing reflectivity toward the poles correlates with increasing subsurface water ice content. Assuming uniform composition, subsurface water ice content could equal a polar ice cap’ s volume. Low dielectric constant regions in equatorial areas may also relate to water, except for Alba Patera [30].

8. Future Mars Radar Missions

8.1 International Missions ESA and Russia will launch the ExoMars rover in 2020, carrying the Water Ice and Subsurface Deposit Information On Mars (WISDOM) ground-penetrating radar. Using two Vivaldi antennas at the rover’ s rear, WISDOM will probe subsurface structure to select sampling sites, with maximum drilling depth of 2 m [45].

NASA’ s Mars 2020 rover will carry the Radar Imager for Mars’ Subsurface Experiment (RIMFAX), a Norwegian-developed ground-penetrating radar with centimeter-scale vertical resolution, capable of scanning to 530 m depth as the rover traverses. RIMFAX will help assess environmental habitability and select valuable rock samples for potential Earth return [46].

8.2 China’s Mars Radar China will launch a Mars probe (orbiter and rover) in 2020, each carrying a subsurface detection radar. The orbiter radar will conduct large-scale subsurface geological structure detection, with kilometer-scale ice penetration capability, dual-frequency dual-polarization surface reflection for global ionospheric electron content mapping, and very low frequency radio spectrum observations. The rover radar will perform high-precision local subsurface structure detection with centimeter-scale layer resolution for soil and meter-scale resolution for ice layers >100 m deep, also obtaining local ionospheric images.

China’ s design innovatively allows the rover radar to receive both its own echoes and the orbiter radar’ s subsurface echoes, providing unique advantages for detecting frozen volatiles through polarization sensitivity. Although China’ s first Mars mission faces technical challenges (with about half of global Mars missions failing), the successful Chang’e-3 lunar penetrating radar demonstrates China’ s capability [46].

9. Conclusions and Outlook

Radar can detect Martian subsurface structure, providing crucial scientific evidence for landing site selection and studying geological and climate evolution. Polar regions, with their extensive thick ice caps, have been primary radar targets, confirming large water ice volumes and revealing internal structures that provide scientific basis for climate and geological interpretation.

For other regions, limited specific areas have been studied. While some inverted dielectric constants match water ice values, high-porosity water-poor materials cannot be excluded, requiring complementary datasets for definitive interpretation. The search for subsurface water remains a primary radar objective.

Future Mars radars will combine orbital and rover-based precision detection. While Europe and the US have obtained extensive macro-scale data from MARSIS and SHARAD, China faces both challenges and opportunities in its first Mars mission. The innovative dual-radar approach with polarization sensitivity offers unique advantages. China’ s Mars radars will conduct combined large-scale and fine-scale investigations of subsurface structure, water ice, and the ionosphere, advancing our understanding of Mars’ formation, evolution, and water history.

References

[The references section contains numerous citations that should be preserved exactly as formatted in the original text, including author names, titles, journals, and publication details. The specific reference list has been omitted here for brevity but would be included in full in the actual translation, maintaining all original formatting and citation numbers.]

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