Data Processing Techniques and Current Status of Mars Orbiter Subsurface Sounding Radar: A Postprint

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Abstract

Mars is one of the important targets for extraterrestrial celestial body exploration. Investigations and studies of the Martian surface have indicated that liquid water once existed on Mars. As water constitutes the fundamental basis and prerequisite for life, searching for various forms of water in the subsurface has become one of the key scientific objectives of current Mars exploration. Over the past seventeen years, the Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) onboard the European Mars Express and the Shallow Radar (SHARAD) onboard the US Mars Reconnaissance Orbiter have conducted extensive investigations of the Martian subsurface. Due to the operational principles of radar, raw echo data acquired by radar must undergo data processing procedures including range and azimuth processing, ionospheric correction, and other steps to achieve imaging, from which scientific information is extracted, yielding numerous scientific achievements. Data processing techniques for Mars subsurface sounding radar have played an indispensable role in Mars subsurface exploration, exhibiting strong representativeness and reference value. This review summarizes current radar-based investigations and research on the Martian subsurface, introduces data processing techniques for Mars subsurface sounding radar, enumerates selected scientific achievements, and prospects forthcoming Mars subsurface sounding radars to be deployed.

Full Text

Research on Data Processing Technology and Current Status of Mars Orbiter Subsurface Investigation Radar

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Abstract: Mars represents one of the most important targets for extraterrestrial exploration. Investigations of the Martian surface have revealed evidence that liquid water once existed there. Since water constitutes the fundamental basis and prerequisite for life, searching for water in various forms within the subsurface has become a critical scientific objective of current Mars exploration missions. Over the past seventeen years, the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) aboard ESA' s Mars Express and the Shallow Subsurface Radar (SHARAD) aboard NASA' s Mars Reconnaissance Orbiter have conducted extensive surveys of the Martian subsurface. Due to the operational principles of radar, raw echo data must undergo range processing, azimuth processing, and ionospheric correction to generate radargrams from which scientific information can be extracted, yielding numerous scientific achievements. Data processing technology has played an indispensable role in Mars subsurface exploration, demonstrating strong representativeness and reference value. This paper reviews current subsurface investigations of Mars using radar, introduces data processing techniques for Mars subsurface investigation radars, presents selected scientific results, and provides an outlook on upcoming Mars subsurface radar missions.

Keywords: radar; Mars; subsurface; range processing; azimuth processing; ionospheric correction
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Mars, a terrestrial planet in our solar system, exhibits greater similarity to Earth in terms of atmosphere and geology compared to Mercury and Venus, making it the most Earth-like planet in the solar system. Since the dawn of the space age, Mars has ranked among the most important targets for extraterrestrial exploration, with a total of 45 flyby, orbiter, landing, and rover missions attempted by the United States, the Soviet Union, and other nations—second only to the 124 missions to the Moon. The first peak in Mars exploration occurred between 1960 and 1975, during which Mariner 4, 6, and 7 conducted flyby missions, capturing close-up images of Mars that provided humanity with clear views of the Martian surface. Mariner 9 achieved the first orbital mission, while Viking 1 and 2 successfully soft-landed on the surface, with the Soviet Union also launching multiple probes during this period. A second peak began after 1992, with missions including Mars Express, Mars Reconnaissance Orbiter (MRO), Mars Global Surveyor (MGS), the Phoenix lander, Spirit, Opportunity, and Curiosity rover arriving at Mars to conduct multi-wavelength optical remote sensing, radar subsurface sounding, and in-situ exploration. These missions have mapped detailed surface morphology, mineral distribution, and brightness temperature patterns, studied subsurface structures, and searched for evidence of liquid water and its past existence.

A series of surface investigations have demonstrated that liquid water once existed on Mars, with subsurface 探测 at the Martian south polar ice cap even providing direct observational evidence. Data collected by the MARSIS radar aboard ESA' s Mars Express between 2012 and 2015 revealed a 20-kilometer-wide liquid water lake located 1.5 kilometers beneath the south polar ice cap. The discovery of water in various states on Mars has intensified the search for traces of past or present life.

A critical instrument in this search for water and biosignatures is the orbiter subsurface investigation radar. Unlike rover-mounted systems, spaceborne radars employ synthetic aperture techniques that enable high azimuth resolution from orbital altitudes of hundreds of kilometers through along-track processing. Orbiter subsurface radars can achieve penetration depths of hundreds to thousands of meters, though with relatively coarse resolution—typically tens of meters. To date, only ESA' s Mars Express (2003) and NASA' s Mars Reconnaissance Orbiter (2005) have carried such instruments, known as MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) and SHARAD (Shallow Subsurface Radar), respectively. In contrast, the rover-mounted subsurface penetrating radar that proved highly successful in China's "Chang' e" lunar program has not yet been deployed on Mars.

China's first Mars exploration mission, formally approved in 2016, launched successfully on July 23, 2020, from Wenchang aboard a Long March 5 rocket. The mission comprises both an orbiter and a rover, each equipped with subsurface investigation radars. NASA' s Mars 2020 mission launched on July 30, 2020, the UAE' s Hope mission on July 20, 2020, and the joint European-Russian ExoMars mission—originally scheduled for 2020 but postponed to 2022 due to the pandemic—marks another peak in Mars exploration. Both Mars 2020 and ExoMars carry rover-mounted subsurface radars. With these missions poised to reach Mars, data processing, analysis, and interpretation will become a major focus and challenge. This paper reviews domestic and international achievements and technical progress in Mars subsurface radar exploration, offering insights for maximizing the scientific return from future mission data.

1. Development of Subsurface Investigation Radar Technology for Mars

Radar' s strong electromagnetic wave penetration capability and independence from solar illumination enable all-weather operation, making it highly valuable for lunar subsurface exploration. The Apollo Lunar Sounder aboard Apollo 17 (1972), the Lunar Radar Sounder on Japan' s SELENE (2007), and the Lunar Penetrating Radar (LPR) on Chang' e-3 and Chang' e-4 rovers have all successfully detected subsurface layering in the lunar maria. The Yutu and Yutu-2 rovers carried identical LPR systems operating at 40-80 MHz and 250-750

MHz, achieving maximum penetration depths exceeding 100 meters with range resolution better than 1 meter. Chang' e-3' s radar estimated regolith depth at 4-6 meters and identified a basalt layer at approximately 330 meters depth. Chang' e-4' s radar in Von Kármán crater achieved even greater depth, revealing three subsurface layers: regolith (12 m), coarse material with embedded rocks (12-24 m), and alternating layers of coarse and fine material (24-40 m).

Mars missions face greater challenges due to distance and energy requirements. Early Mars exploration relied primarily on optical instruments, with radar rarely employed. Currently, both ground-based radar observations and orbiter subsurface radars are used operationally, though no rover has yet carried a subsurface penetrating radar. China' s Mars rover and NASA' s Mars 2020 Perseverance rover will deploy the first such instruments on Mars.

Ground-based radar initially employed the 305-meter Arecibo telescope in Puerto Rico and the 70-meter Goldstone radio telescope in California. Using stochastic long-code delay-Doppler and interferometric delay-Doppler techniques during Mars opposition, these systems obtained surface elevation, reflectivity, roughness, and dielectric constant information. However, Mars' s rapid rotation causes severe Doppler frequency shifts that complicate observations, and ground-based techniques cannot probe the subsurface. With the advent of orbital and landed missions, ground-based radar has transitioned to supporting roles such as landing site selection.

The scientific objective of locating various forms of water in the subsurface has driven advances in subsurface radar technology, elevating its importance in mission payloads. Mars subsurface radars have now acquired near-global coverage, identifying water ice deposits and generating high-value scientific results that inform hypotheses about Mars' s climatic, geological, and orbital evolution.

1.1 Orbiter Subsurface Investigation Radar

Subsurface investigation radars can penetrate the Martian surface to probe its internal structure. Electromagnetic waves emitted by the radar can partially penetrate soil, ice, and rock, reflecting, scattering, and transmitting at interfaces between media with different dielectric constants. This capability enables detection of geological layering such as dry soil-ice boundaries, glacier-bedrock interfaces, ice- or water-filled porous rocks, and subglacial liquid water. However, electromagnetic waves experience attenuation as they propagate through media, with absorption generally dependent on the medium' s dielectric constant and the wavelength. Longer-wavelength, lower-frequency waves experience less attenuation and achieve greater penetration depth. Consequently, subsurface radars typically operate between 1 MHz and 1 GHz, though bandwidth determines resolution—smaller bandwidth yields higher depth resolution. These competing requirements impose significant constraints on radar design.

MARSIS operates in subsurface mode across four sub-bands from 1.3-5.5 MHz, each with 1 MHz bandwidth (1.3-2.3 MHz, 2.5-3.5 MHz, 3.5-4.5 MHz, 4.5-5.5

MHz), corresponding to vacuum wavelengths of 55-230 m. SHARAD operates at 15-25 MHz with 10 MHz bandwidth (12-20 m wavelength). These parameter differences result in distinct performance characteristics (Table 1).

Table 1. Main Performance Parameters of MARSIS and SHARAD [10-14]

Parameter	MARSIS	SHARAD
Orbit altitude (km)	250-800	250-320
Antenna length (m)	40	10
Frequency band (MHz)	1.3-5.5	15-25
Bandwidth (MHz)	1	10
Transmitter Power (W)	1.6-5	10
Pulse length (s)	250	85
Pulse repetition frequency (Hz)	130	700
Range resolution (m)	150 (vacuum)	15 (vacuum)
Horizontal resolution in along-track (km)	5-10	0.3-1
Horizontal resolution in cross-track (km)	30-50	3-7
Penetration depth (km)	3-5	0.5-1

1.2 Principles of Orbiter Subsurface Investigation Radar

In subsurface sounding, electromagnetic waves transmitted from the orbiter' s antenna traverse the Martian atmosphere, where the ionosphere affects amplitude and phase, before reaching the surface. A portion reflects or scatters back to the antenna, while another portion penetrates the surface, traveling through subsurface media and reflecting at interfaces with different dielectric constants. For an orbiter at altitude H, with c as the speed of light in vacuum, the surface echo from nadir arrives at time delay $\tau = 2H/c$. Subsurface waves propagate at reduced speed $v = c/n$ (where n is refractive index), so an echo from interface depth h arrives at $\tau = 2(H + nh)/c$. Due to the radar' s wide beamwidth, surface echoes include both nadir reflections and off-nadir clutter that may overlap temporally with subsurface returns, potentially masking weaker subsurface signals. Effective subsurface detection therefore requires pulse compression with sidelobes far below the main lobe to distinguish subsurface echoes from surface clutter.

Orbiter radars achieve azimuth resolution through synthetic aperture techniques, as physical antenna apertures large enough for adequate resolution would be impractical in space. The synthetic aperture can be considered as $L = \sqrt{(\lambda R)}$, where λ is wavelength and R is slant range. Substituting into the resolution formula yields optimal azimuth resolution of $\delta = \sqrt{(\lambda R)}/2$ [14], demonstrating why azimuth processing is essential for orbiter subsurface radars.

In practice, antennas and receiver channels introduce amplitude and phase distortions, while ionospheric phase distortion significantly degrades image quality.

Correcting these amplitude-phase errors is critical for imaging accuracy and subsurface detection effectiveness.

1.3 Data Processing Flow and Methods

Synthetic aperture radar processing typically divides into range and azimuth (or Doppler) processing. MARSIS' s common SS3 (subsurface 3) mode performs azimuth processing onboard before downlinking data for ground-based range processing. SHARAD preprocesses raw data onboard with pre-summation, then performs range processing followed by azimuth processing, with different ionospheric correction methods.

1.3.1 Range Processing Range processing involves pulse compression via matched filtering, correlating received echoes with the transmitted signal to concentrate dispersed energy temporally, narrowing echo width and compressing energy. MARSIS and SHARAD implement this differently.

MARSIS Pulse Compression: 1. Perform 512-point FFT on echo signal 2. FFT the reference chirp signal, conjugate its spectrum 3. Multiply echo and reference spectra, then inverse FFT [15]

Since antennas, channels, and ionosphere introduce amplitude-phase variations, using an ideal chirp reference fails to match echo phase, degrading compression. MARSIS therefore derives its reference from ideal chirp convolved with measured instrument calibration distortions, further adjusted for ionospheric effects. Hanning windowing reduces sidelobes at the cost of main lobe broadening.

SHARAD Processing: Two processing chains exist. The first uses reference signals based on antenna matching network calibration data (function of receiver/transmitter temperature), followed by phase-gradient autofocus (PGA) for ionospheric correction. The second employs equal-amplitude frequency component modeling, resulting in asymmetric sidelobe bias where larger time-delay sidelobes have greater amplitude. This approach maintains double oversampling after compression, facilitating subsequent interpolation. Both chains apply Hanning windowing and use a frequency-dependent phase error model linearly related to Total Electron Content (TEC), suitable for images acquired at solar zenith angles $<100°$.

1.3.2 Azimuth Processing Azimuth processing is the key challenge in SAR, with computational requirements varying by algorithm. Orbiter subsurface radars adapt conventional SAR algorithms including Chirp Scaling (CS) [18], ω-k [18], Range-Doppler (RD) [19], and Back-Projection (BP) [20]. Non-focused imaging can use Doppler beam sharpening [17].

The RD algorithm, developed in the late 1970s and still widely used, performs range compression, azimuth FFT to the Doppler domain, sinc-interpolation for range cell migration correction (RCMC), and azimuth compression. While efficient through 1D frequency-domain operations, its interpolation limits accuracy for long apertures and incurs high computational cost.

The CS algorithm avoids interpolation by using phase multiplication for RCMC, decomposing migration into range-independent (bulk) and range-dependent (differential) components. Processing involves azimuth FFT, differential RCMC compensation via phase multiplication, 2D FFT, reference function multiplication for range compression and bulk RCMC, followed by inverse transforms. The ω-k algorithm excels for wide apertures or large squint angles, using 2D FFT, reference multiplication for partial focusing, and Stolt interpolation for complete focusing [18].

SHARAD employs the CS algorithm, decomposing Doppler frequency shift into bulk and differential RCMC components corrected separately. This requires only FFTs and complex multiplications [15], offering computational efficiency. The process: (1) calculate RCMC by arranging each range bin relative to aperture center; (2) azimuth compression using orbital altitude, radial velocity, and tangential velocity to determine differential phase (using 25 MHz maximum frequency for optimal focus); (3) FFT of corrected "iso-range lines" with Hanning windowing for sidelobe suppression, generating 128 image columns per ~460 m (1° interval). Multi-look processing is possible when Doppler bandwidth exceeds a frequency resolution cell.

MARSIS uses Doppler beam sharpening—a non-focused SAR technique with lower azimuth resolution but reduced computation. After compensating vertical motion, it stacks all same-frequency echoes within a frame (containing echoes over one synthetic aperture time), adjusting phase for coherent summation. This creates a Doppler filter bank for subsequent ground-controlled selection of either the leading-edge reflection method or contrast method for ionospheric phase correction of the central Doppler filter (Filter 0), with results used to update range compression reference functions (Figure 2 [Figure 2: see original paper]).

China' s Tianwen-1 orbiter subsurface radar (MOSIR) initially adopted the BP algorithm for real-time onboard imaging due to its straightforward implementation, though ground processing of downlinked raw data may select alternative methods based on data characteristics and imaging quality.

1.3.3 Ionospheric Correction MARSIS' s operating frequencies are close to Mars' s ionospheric plasma frequency [16], making ionospheric effects on echo delay, amplitude, and phase non-negligible. Initial processing used two methods: leading-edge reflection and contrast method, with literature favoring the contrast method [17] (Figure 3 [Figure 3: see original paper]). The contrast method estimates dominant coefficients from Taylor expansion of ionospheric phase error, iteratively pulse-compressing with applied corrections until maximum energy concentration is achieved, then calculates TEC from the final coefficients [21].

SHARAD' s higher frequencies experience attenuation and group delay in the ionosphere (plasma frequency ~few MHz). Onboard processing uses PGA for phase error correction, a method also later applied to MARSIS as a complement to the contrast method [22]. PGA simultaneously estimates ionospheric and other phase errors by selecting bright, uncompensated frames as prominent points, using defocused image phase redundancy for robust gradient estimation through circular shifting, windowing, gradient estimation, and iterative correction. PGA performance depends heavily on prominent point selection; unstable dominant Taylor coefficients degrade correction effectiveness.

1.4 MARSIS & SHARAD Imaging Comparison

Parameter differences yield distinct capabilities: MARSIS's lower frequency, narrower bandwidth, longer wavelength, and non-focused Doppler beam sharpening provide deeper penetration (up to 3 km) but coarser resolution in all dimensions —particularly range resolution, where SHARAD' s theoretical value is ten times better. SHARAD's higher frequency and wider bandwidth achieve shallower penetration but finer resolution. Their data are complementary: MARSIS provides large-scale regional mapping to identify targets for SHARAD' s high-resolution imaging of subsurface structures hundreds of meters deep.

A comparison of MARSIS orbit 3749 and SHARAD orbit 2026 over similar regions [15] shows SHARAD clearly imaging subsurface interfaces ~7 s below surface (hundreds of meters depth) with fine detail, though shallower than MARSIS, consistent with theoretical predictions (Figure 4 [Figure 4: see original paper]).

1.5 Research Status

After nearly two decades of operation, MARSIS and SHARAD have achieved near-global coverage, with data still being released as of 2019. Researchers integrate Mars Orbiter Laser Altimeter (MOLA) digital elevation models (spatial resolution ~1°, absolute accuracy 13 m [23]) to simulate surface clutter, filtering it from mixed subsurface echoes [24][25]. Extracted subsurface returns, combined with terrain analysis, enable dielectric constant and attenuation coefficient inversion, interface depth estimation, and material composition speculation, yielding high-value results that inform hypotheses about Mars' s climatic, geological, and orbital evolution.

North Polar Region: MARSIS first probed the North Polar Layered Deposits (NPLD), a ~600 km diameter region of water ice with minor dust comprising three units: North Residual Ice Cap (NRIC), NPLD, and Basal Unit. Analysis of early 3 MHz and 5 MHz data from orbit 1855 [26] showed split surface echoes crossing the NPLD margin. MOLA-based clutter simulation excluded off-nadir clutter, confirming the lower echo as subsurface. Time delay and relative strength indicated basal material dielectric properties consistent with pure water ice (~3). Converting delay to depth yielded 1.8 km, matching NPLD elevation above surroundings, proving a thick elastic lithosphere and low crust-mantle temperature gradient (Figure 5 [Figure 5: see original paper]).

South Polar Region: Similar to the north, the South Polar Layered Deposits (SPLD) comprise SRIC, SPLD, and Dorsa Argentea Formation (DAF). Orbit 2753 data [27] also showed split echoes at the SPLD margin, with the lower echo —when converted using water ice dielectric constant—aligning with surrounding terrain extension, interpreted as the ice-rich SPLD/rocky basement interface. MARSIS detected this interface across most of SPLD. In some regions (e.g., orbit 2682), basal echoes exceeded surface echo strength, indicating extremely low attenuation (tan δ ~0.001-0.005) and dust content <10% (Figure 6 [Figure 6: see original paper]). Comprehensive SPLD coverage enabled thickness mapping by subtracting MARSIS basal elevations from MOLA surface elevations (Figure 7 [Figure 7: see original paper]).

Subglacial Liquid Water: MARSIS' s most significant discovery came from SPLD. Data centered at 193°E, 81°S (200 km wide) showed unusually strong basal reflections exceeding surface echoes in some areas (Figure 8 [Figure 8: see original paper]). Normalized basal echo strength mapping revealed a 20 km wide anomalous zone. Electromagnetic simulation of geological structure yielded permittivity >15, suggesting subglacial liquid water stabilized by perchlorate salts (Figure 9 [Figure 9: see original paper]) [28].

Medusae Fossae Formation: MARSIS data (130°-240°E equatorial region) studied this potentially youngest depositional unit (~2.1$\times10^{6}$ km^2), detecting subsurface interfaces that support previous volume estimates (1.4-1.9$\times10^{6}$ km^3). Measured dielectric constant (2.9$\pm$0.4) *andattenuationcoefficient*(0.0048$\pm$0.0024 dB/m) suggest dry porous material or ice-dust mixtures with higher dust content than SPLD (Figure 10 [Figure 10: see original paper]) [29].

Lobate Debris Aprons (LDAs): SHARAD' s higher resolution reveals features MARSIS cannot detect. Over 100 tracks in Deuteronilus Mensae' s fan-shaped deposits showed split echoes crossing LDAs, with the lower echo confirmed as subsurface (Figure 11 [Figure 11: see original paper]). Dielectric constant (~3) and attenuation rate (~2 dB/ s) match relatively pure water ice or ice-mineral mixtures [30]. Similar LDAs at 30°-60° latitude in both hemispheres were studied in Hellas basin [31], showing uniform subsurface media without large rock fragments, attenuation $ $10 dB/km consistent with pure ice and dust content <10% (Figure 12 [Figure 12: see original paper]).

Utopia Planitia: This ~3300 km diameter northern lowland region exhibits polygonal and scalloped terrain suggesting near-surface ice. SHARAD data combined with MOLA topography estimated subsurface dielectric constant of 2.8$\pm$0.8, *consistentwithwaterice−rock−airmixturescontaining*50−85^{3}$ of water ice [32].

Polar Layering: SHARAD resolved meter-scale layering in SPLD' s Promethei Lingula (Figure 13 [Figure 13: see original paper]), identifying interfaces at 130-420 m, 340-450 m, 450-570 m, and 890-1030 m depth [33]. North polar data (orbit 5192) mapped stratigraphy showing ice-dust-sand interfaces, basal unit detection, and spiral troughs hundreds of meters deep, confirming Gemina

Lingula' s NPLD directly overlies Vastitas Borealis Formation without basal unit, supporting thick lithosphere hypotheses (Figure 14 [Figure 14: see original paper]) [34].

2. Future Mars Exploration Radar Payloads

The 2020 launch window saw missions from China, the US, UAE, and private enterprises, with Europe' s ExoMars postponed to 2022. Both Chinese and US rovers carry subsurface radars, as does China' s orbiter.

2.1 Foreign Radar Payloads

RIMFAX (Radar Imager for Mars Subsurface eXperiment) aboard Perseverance aims to image subsurface geology and composition, revealing stratigraphic history of impact, aeolian, and fluvial processes [35]. The ultra-wideband bow-tie slot antenna, mounted on the rover' s rear lower section, switches between transmit and receive modes. Operating at 150-1200 MHz in gated-FMCW mode, RIMFAX scans three sub-bands (150-300 MHz, 300-600 MHz, 600-1200 MHz) with 1-20 ms sweep time. It images >10 m depth with <30 cm vertical resolution and 10 cm horizontal sampling along the rover path [35].

Three operational modes accommodate dynamic range limitations: Surface mode includes antenna self-reflection and surface echo; Shallow mode excludes self-reflection, covering surface and shallow reflections; Deep mode places all near-surface echoes outside the dynamic window [36].

Field tests in Svalbard, Norway (2015, 2016) on cold temperate glaciers validated performance. The 2015 data used Blackman-Harris windowing and zero-padding (Figure 15 [Figure 15: see original paper]), while 2016 added background removal (Figure 16 [Figure 16: see original paper]) [35][36].

WISDOM (Water Ice and Subsurface Deposit Observations on Mars) on ExoMars' s Rosalind Franklin rover aims to study 3D geological structure, evolution, and water distribution [37]. This UHF step-frequency radar (500 MHz-3 GHz, 2.5 GHz bandwidth) transmits continuous waves at each frequency for 200 s steps [37]. With N_f = 1001 frequencies and spacing Δf determining maximum unambiguous range, WISDOM achieves centimeter-scale vertical resolution [38]. Data undergo Hilbert transform (90° phase shift, applicable to single-frequency steps), inversion to complex transfer function, and inverse FFT to time domain. Windowing reduces range sidelobes and enhances SNR (Figure 17 [Figure 17: see original paper]).

Field tests in Atacama Desert, Etna volcano, Alpine glaciers, and Dachstein ice caves demonstrated capability to resolve fine structures. In Atacama, WISDOM detected a buried channel bed ~50 cm deep and 7 m wide (Figure 18 [Figure 18: see original paper]) [37]. Etna tests after rainfall showed clear subsurface interfaces to 3 m depth with 10 cm sampling [39]. Directional antenna patterns enable dual-polarization configurations for 3D reconstruction of subsurface interfaces (Figure 19 [Figure 19: see original paper]) [37].

2.2 Domestic Radar Payloads

China' s Tianwen-1 mission, launched July 23, 2020, ambitiously combines orbiter and rover, each carrying subsurface radars developed by the Institute of Electronics, Chinese Academy of Sciences (rover) and the 38th Research Institute of China Electronics Technology Group (orbiter). Both employ dual-frequency, dual-polarization configurations for deep penetration and high precision, with polarization capability offering new avenues for water ice detection.

2.2.1 Rover Subsurface Penetrating Radar (RoSPR) The Rover Subsurface Penetrating Radar (RoSPR) performs ultra-wideband full-polarization sounding using linear frequency-modulated signals [40]. Low-frequency mode: 55 MHz center, 80 MHz bandwidth, 145 s pulse width, 5 ms PRF. High-frequency mode: 1300 MHz center, 1700 MHz bandwidth, 4 ms pulse width, 5 ms PRF. Estimated performance: low-frequency penetration 1125 m (= 4), resolution 0.94 m; high-frequency penetration 30 m (= 4), resolution 4.4 cm.

Low-frequency uses dipole antennas under the rover deck (HH polarization only). High-frequency employs Vivaldi antennas on the front panel in orthogonal polarizations, enabling HH, HV, VH, VV full-polarization by alternating transmit polarizations and selecting receive polarization (Figure 20 [Figure 20: see original paper]).

Validation tests included a 7$×3×$2.5 m pool filled with artificial volcanic ash (= 2.8-3.2) containing buried pipes and rocks (Figure 21 [Figure 21: see original paper]). High-frequency mode data after removing rover multipath and background subtraction clearly identified pipe and bottom echoes (Figure 22 [Figure 22: see original paper]) [41]. Field tests in loess (Yulin), glaciers (Laohugou), and volcanic fields (Ulan Had) in 2018-2019 validated both modes. Unlike Chang' e LPR' s pulse signals, RoSPR' s chirp signals require different processing flows.

2.2.2 Orbiter Subsurface Investigation Radar (MOSIR) The Mars Orbiter Subsurface Investigation Radar (MOSIR) shares similarities with MARSIS/SHARAD but offers dual-frequency, dual-polarization capability. Polarization enables Stokes parameter calculation for water ice detection and ice cap property characterization—impossible with single-polarization radars. MOSIR operates in Very Low Frequency, Low Frequency, High Frequency, and Altimetry modes, all using chirp signals with varying parameters (Table 2).

Table 2. Performance and Operating Parameters of MOSIR Modes

Parameter	High Frequency Subsurface	Low Frequency Subsurface	Altitude Detection
Pulse length (s)	70 (LF) / 120 (HF)	70 (LF) / 120 (HF)	70
Data window duration (s)	120 (LF) / 170 (HF)	120 (LF) / 170 (HF)	120
Center frequency (MHz)	12.5 / 17.5	12.5 / 17.5	12.5
Frequency band (MHz)	5 / 10	5 / 10	5
Sampling rate (MHz)	20 / 40	20 / 40	20
Pulse repetition frequency (h=265km, Hz)	200 / 400	200 / 400	200
Free-space range resolution (m)	30 / 15	30 / 15	30
Horizontal resolution in along-track (km)	2.5 / 1.5	2.5 / 1.5	2.5
Horizontal resolution in cross-track (km)	5-10	5-10	5-10

Parameter	High Frequency Subsurface	Low Frequency Subsurface	Altitude Detection
Penetration depth (km)	1-3	1-3	-

Downlinked data offers flexibility: raw data can be processed on ground, or onboard-processed images can be transmitted. For raw data, after unpacking and classification, channel/antenna calibration coefficients and ionospheric compensation factors are calculated from high/low-frequency nadir echoes using methods from [20]. These are multiplied with windowed standard compression coefficients to generate reference functions that simultaneously perform pulse compression, channel compensation, antenna response correction, and ionospheric correction. Post-compression, the BP algorithm is initially selected for focusing. BP projects echo data onto each image pixel by calculating corresponding delays: at each FR position, compute orbiter coordinates and distances to 21$\times$300 focus points, bin pulse-compressed data by range cell (6.25 m in HF), phase by wavelength (7.5 m in HF), apply complex multiplication and Doppler windowing, then accumulate. MOSIR can also calculate TEC from time differences between high- and low-frequency nadir echoes.

In 2019, MOSIR underwent field validation in Dengkou County, Inner Mongolia, using a balloon-suspended orbiter model. Tethered flights calibrated antenna isolation and gain; free flights validated altimetry mode precision (<10 m after terrain correction) and data compression/processing flows.

3. Summary and Outlook

Radar' s low-frequency penetration capability and independence from illumination enable investigation of permanently shadowed regions, offering significant value for lunar, planetary, and asteroid exploration of subsurface structure and water ice. However, radar' s reliance on transmitted/reflected waves necessitates extensive processing to reveal physical quantities, with ionospheric effects further complicating orbital sounding. Orbiter subsurface radars universally employ SAR technology requiring range and azimuth processing. Numerous algorithms have emerged since SAR' s inception: CS, beam sharpening, ω-k, RD, etc., with CS and beam sharpening currently operational on SHARAD and MARSIS, and PGA/contrast methods used for ionospheric correction.

Beyond imaging, MARSIS and SHARAD research integrates MOLA topography for clutter simulation and employs multiple methods to invert dielectric constants, attenuation coefficients, and interface depths, yielding major discoveries. With MARSIS and SHARAD' s extensive coverage and achievements, China' s MOSIR—despite being a first-generation planetary radar—benefits from this technical heritage and has potential for significant contributions. Rover radars, while using different architectures, build on Yutu' s successful legacy. We anticipate that China' s Tianwen-1 radars will return crucial scientific information about Martian subsurface structure and water ice, playing a vital role in planetary science.

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