Numerical Simulation of Subsurface Penetrating Radar in Isidis Planitia on Mars for China's First Mission to Mars

Ying Wang1,2, Xuan Feng1,2,3,4,*, Wenjing Liang1,2, Haoqiu Zhou1,2, Zejun Dong1,2, Xiaotian Li1,2, Cewen Xue1,2
1 College of Geo-Exploration Science and Technology, Jilin University, No.938 Xi Min Zhu Street, Changchun, China
2 Science and Technology on Near-Surface Detection Laboratory, Wuxi, China
3 Institute of National Development and Security Studies, Jilin University, No.2699 Qianjin Street, Changchun, China
4 Key Laboratory of Geophysical Exploration Equipment, Ministry of Education (Jilin University), No.938 XiMin Zhu Street, Changchun, China
*E-mail: fengxuan@jlu.edu.cn.

Abstract-The water ice exploration mission is an important scientific target of China's first Mission to Mars. The high frequency full polarimetric subsurface penetrating radar (SPR) system onboard the landing rover can carry out high-resolution imaging of the near-surface area of Mars, which is an important tool for detecting the presence of shallow water ice and soil structure. At present, most of the radar detection simulations are based on low-frequency antennas to analyze the geological structure of Mars down to several kilometers, with low resolution, which is difficult to detect the subsurface structure in the near-surface accurately. Considering topographic relief, interface roughness, subsurface rock, water ice, and permittivity changes at different layers, a three-dimensional near-surface model in the Isidis Planitia on Mars is established. The interpretation of the forward simulation results is of reference value for future Mars exploration missions.

1. Introduction
Extensive researches on Martian landforms and surface composition suggest the presence of surface water on the planet in the past. However, due to considerable geological change over its history, the planet becomes frigid conditions of today, and the water that has been detected so far is found in the polar ice caps and subsurface [10,13]. Sylvain Piqueux derived the depth of the shallow water ice table on Mars at high and mid latitudes by fitting seasonal subsurface temperature trends acquired by the Mars Climate Sounder and Thermal Emission Imaging System [11]. The current Martian hydrological model shows that due to the low temperature, the surface water ice can stably exist in areas with latitude greater than 40° in contact with the atmosphere, while ice in low latitude areas can be stable at a depth of 1 ~ 2 m [2,4,6].

So far, many scholars have interpreted the data acquired from Mars-orbiting radar, including the detection of the interior structure of Planum Boreum [8] and South Polar Layered Deposits [9], the deposition thickness and dielectric properties of Medusae Fossae Formation [12], and the buried glaciers exist in the southern mid-latitudes of Mars [3]. Simulation of the Mars subsurface structure is instructive for data processing. Leuschen considered the simulation and design of a ground-penetrating radar system to probe the Martian subsurface for aqueous layers in either liquid or solid state [5]. Carl
Leuschen developed a radar simulator to model the response for various geological conditions, which is capable of modeling the effects of dielectric layering, volume debris, frequency dispersion, ohmic losses, and interface roughness [1].

China’s first Mars exploration mission will launch an orbiter and a landing rover in 2020. The landing rover carrying a subsurface penetrating radar (SPR) instrument may land in Chryse Planitia or Isidis Planitia [14]. The SPR consists of two channels to characterize the thickness and sub-layer distribution of the Martian soil, of which one will operate at a 35 MHz to 75 MHz and the other will operate in a 0.8 GHZ to 1.8 GHz frequency band [16].

In this paper, a 3-D Mars near-surface model is first built. The former papers are based on low-frequency antennas to analyze the geological structure of Mars down to several kilometers, with low resolution, which is difficult to detect the subsurface structure in the near-surface accurately. For the purpose of detect the shallow buried water ice at low latitudes, considering topographic relief, interface roughness, subsurface rock, water ice, and permittivity changes at different layers, we established a three-dimensional near-surface model of Mars. The model consists of four layers simulating a zone from air to two-meter underground. Then the finite-difference time-domain (FDTD) approach was used to simulate the electromagnetic response. Through observing numerical simulation, we can estimate the relative permittivity of different layers and distinguish lumpy ice from rocks, which is of reference value for future Mars exploration missions.

2. Tentative landing area on Mars and subsurface penetrating radar aboard on the rover

There are two sub-area in the latitude range of 5°-30° are selected to be the tentative landing area for the China’s first Mars exploration mission by 2020. One is located in Chryse Planitia, while the other one is in Isidis Planitia and stretches to the western edge of the Elysium Mons region [14], as shown in Figure 1. Considering the difficulty and safety of the landing, we prefer to choose area 2 for high-precision landing detection.

![Figure 1. Tentative landing area on Mars (quoted from Ye et al., 2017)](image-url)

The SPR aboard on the rover consists of two channels, the first one is a single polarimetric radar operates in a 35 MHz to 75 MHz frequency band, the second one is a full polarimetric radar operates at 0.8 GHZ to 1.8 GHz [16]. Both of them are installed in the front of the Mars rover (fig. 2) [17]. The two radars on the rover are used to detect the thickness of the soil, subsurface structure and ice layer structure in the roving area [14].
3. Modeling process
The previous researches reveal that the surface of Mars is dominated by basalts, which may show a small amount of andesite [7]. For Mars near-surface modeling, considering topographic relief, interface roughness, subsurface rock, water ice and permittivity changes at different layers, we established a three-dimensional near-surface model of Mars, as shown in Figure 3. The near-surface model is eolian sediment overlying the basalt layer. As water ice may be present underground, the eolian sediment is further divided into dry sediments and ice-containing sediments. Some rocks and lumpy ice exist in the sediment. In the modeling process, “Diamond-Square Algorithm” was used to generate stochastic fractal terrain, abrasive grains were used to generate irregular rocks [18]. The details of the 3-D near-surface model of Mars are shown in Table 1.

![Figure 3. Three-dimensional near-surface model of Mars.](image)

![Figure 4. Two-dimensional near surface model extracted from 3-D Mars near-surface model at y=0.37 m.](image)

| Interface information | Interface                     | Fluctuation range (m) | Roughness H |
|-----------------------|-------------------------------|------------------------|-------------|
|                       | Regolith surface              | 0.1                    | 1           |
|                       | Eolian sediment(dry/icy)      | 0.2                    | 1           |
|                       | Icy eolian Sediment/Layered basalt | 0.3       | 1           |

| Rock & Water ice      | Quantity | Size(m) | Relative permittivity |
|-----------------------|----------|---------|-----------------------|
| Rock                  | 21       | 0.05-0.35 | 3.5                  |
| Water ice             | 3        | 0.1-0.3  | 3.15                 |

| Layer information     | Depth(m) | Relative permittivity |
|-----------------------|----------|-----------------------|
| Regolith              | 0-0.1    | 2.4                   |
| Dry eolian sediment   | 0.1-0.85 | 2.8                   |
| Icy eolian sediment   | 0.85-1.55| 5.1                   |
| Ice-bearing basalt formation | 1.55-2  | 6.9                   |

Table 1. Parameters of the 3-D near-surface model of Mars
4. Numerical Simulation & analysis

Our purpose is to detect the structure of the soil and the water ice it may contain, whose thickness may less than 2m in Isidis Planitia. The antenna central frequency used in simulation is 1300 MHz (CH2), whose penetration depth is 3 to 10 m with a resolution of a few centimeters within the Martian soil [16]. The CH2 transceiver antenna is mounted in the front of the rover, which is about 30 cm above the ground.

In this paper, we use 3-D FDTD to perform forward modeling of the near-surface model, which can obtain more underground information. Since 3-D FDTD has a huge amount of calculations, we reduce the size of the model in the y direction and built a model with a length of 4.5 m in the x direction, 0.8 m in the y direction, and 2 m in the depth direction. As the antennas are 0.3 m above the ground, a 0.4m thick air layer was established above the ground. We choose to perform forward modeling along the x direction at y equal to 0.37 m; the corresponding 2-D model can be seen in Figure 4. Some specific parameters of the simulation are shown in Table 2.

The simulation result is shown in Figure 5a. After the preprocessing process, including automatic gain control, filtering direct waves, and bandpass filtering, the processed results are shown in Figure 5b. From Figure 5b, we can identify the existence of two interfaces in the subsurface (shown by arrows in fig. 5b) and reflections caused by anomalous bodies. In order to converge the diffraction wave to the diffraction point where it was generated, Kirchhoff migration was used in processing. Because the electrical parameters of layers are different, different velocities are selected for the first layer and the second layer to produce better migration image. We select the velocity of 0.2 m/ns and 0.18m/ns for migration respectively, and analyze the information of the first layer from the first result, and the second result is used to analyze the information of the second layer.

Table 2. Simulation parameters

| Antenna Height | Transceiver antenna distance | Dominant frequency | Source type | Waveform |
|----------------|-----------------------------|-------------------|-------------|----------|
| 0.3m           | 0.3m                        | 1.3GHZ            | Point source | Ricker wavelet |
| Absorbing boundary Type Thickness | | | | 0.15 m |
| Discretization grid | Time step | Time window | Measuring points |
| 0.01 m × 0.01 m | 0.01ns | 31ns | 0:04:4.48 |
| Discretization grid | Time step | Time window | Measuring points |
| 0.01 m × 0.01 m | 0.01ns | 31ns | 0:04:4.48 |

Figure 5. a. Forward simulation result of near-surface model; b. Preprocessed results of raw data. The green and red arrows indicate the interface between dry and icy eolian sediment, and the interface between icy eolian sediment and basalt, respectively.
We analyze the information in first layer through Figure 6a as follows.

1) The dielectric constant of layer 1 is inferred from the velocity to be 2.25;
2) The interface is 0.87 m underground, and the fluctuations are consistent with the model;
3) Many reflected waves caused by rocks can be seen. Compared with the model, the red arrows indicate the rocks below the survey line, and the blue arrows indicate the rocks existing in adjacent areas. Reflected waves from small rocks close to the surface are masked by surface reflections and cannot be identified.
4) At the same depth, even if the rock is not directly below the survey line, it will cause reflected waves with similar intensity.

![Figure 6a](image1.png)

![Figure 6b](image2.png)

**Figure 6.** Result of processing by Kirchhoff migration. The red arrows indicate the rocks below the survey line and the blue arrows indicate the rocks existing in adjacent areas. The hyperbola in the red square means water ice in the 2-D profile, the hyperbola in the blue square represents water ice in the surrounding area, and the hyperbola in the orange square is misunderstood water ice.

Using the same method as above, the dielectric constant of layer 2 is 2.78. With reference to Figure 5b and Figure 6b, it can be found that the intensity of the reflected wave at the square position is much weaker than the surrounding reflected waves. It is explained that the electrical parameters here are closer to the soil, and it is speculated that it is water ice contained in the soil. Compared with the model, the hyperbola in the red square means water ice in the 2-D profile, the hyperbola in the blue square represents water ice in the surrounding area, and the hyperbola in the orange square is misunderstood water ice. The reason for this analysis is that the rock is near absorptive boundary, failed to generate complete reflected wave. Red and blue arrows still indicate rocks in and outside the profile. The lower interface of the second layer is 1.67 m underground.

Since the third layer does not contain any reflectors, it is presumed to be a basalt layer.

5. Conclusions
In this study, a 3-D near-surface model with a depth of 2 m was established based on the geological conditions of Isidis Planitia. 3-D FDTD method was used to perform forward modeling along the x direction at y equal to 0.37m. From the study, we found that it is possible to get the dielectric constants of the first and second layers in the model, the existence and location information of rocks and water ice, and the basement of the basalt. The above analysis will help us interpret Mars radar data and analyze Mars underground information in the future.

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