EXPLORATION SUBSURFACE STRUCTURE OF THE MOON: POTENTIAL SCIENTIFIC RETURN FROM A GROUND PENETRATING RADAR.

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Introduction: Subsurface structure of the Moon, at a depth from a few meters to hundreds of meters, not only provides important information concerning significant questions about the geologic and thermal history of the Moon, but also is critical for quantifying potential resources for future lunar exploration and engineering constrains for human outposts.

Recently, with a renewed interest in lunar exploration, a variety of remote sensing instruments, including the Earth-based Arecibo radar [1], the Kaguya lunar radar sounder (LRS) [2], the Chang-E 1 microwave radiometers [3], and the Mini-SARs onboard Chandrayaan-1 and Lunar Reconnaissance Orbiter (LRO) [4,5], have been used to investigate lunar subsurface structure. Preliminary observations have been used to study global and regional regolith thickness [3,6], and deep stratigraphic structure [2]. However, explanations of these data usually depend upon the employed geophysical models, and sometimes are even ambiguous. In addition, interpretations of these observations have to be validated by in situ measurement before confident conclusions can be extended globally.

Ground penetrating radar (GPR) is an important tool for probing the shallow subsurface in a variety of geologic settings [7]. In China's Chang-E 3 lunar mission, a rover deployed GPR will be used to characterize near surface geology, structure and the dielectric properties of the Moon. In this study, we first discussed the scientific rationale for a lunar GPR and the main factors that affect a GPR performance. Then taking Sinus Iridum region as an example, radargrams are simulated using geometrical optics approach. Finally, the potential scientific return from GPR echoes is also discussed.

Factors Affecting GPR Performance: An impulse GPR using a transmitted radar wave can delineate subsurface interfaces between materials with contrast of dielectric and/or structural properties. Penetration depth and range resolution are two major factors for designing a GPR for the Moon. The nominal penetration depth depends on the complex dielectric constant of the lunar material and GPR frequency, whereas the range resolution depends on the real part of the dielectric constant and the GPR bandwidth. Therefore, the dielectric property of the subsurface materials is a key parameter for the design of a lunar GPR.

A recent estimation of the dielectric constant of the Moon shows that the real part varies from 2.5 to 3.4 and the loss tangent varies from 0.0036 to 0.028 [8]. Penetration depth of radar wave varies from 3 to 10 wavelengths over Maria, with a with a minimum located at Oceanus Procellarum and Mare Tranquillitatis, and that over highlands is about 20-25 wavelengths. A VHF and P band frequency can penetrate lunar subsurface from several to tens of meters. Taking the bandwidth of 100 MHz as an example, the range resolution in lunar subsurface varies globally from 0.8 to 0.95 m.

Given the scientific objective and technique feasibility, a dual frequency GPR at 450 MHz and 60 MHz, with a nominal penetration depth roughly from 2 to 50 m for maria and 100 m for highlands, might be a better choice for Chang-E 3 rover. The range resolution in lunar subsurface varies from 20 cm over maria to that of 25 cm over highlands for a bandwidth of 400 MHz (for high frequency band), whereas from about 2 m to 2.5 m for a bandwidth of 40 MHz (for low frequency band).

Preliminary Simulation Results: In this study, the geometrical optics approach is used to simulate GPR echo from lunar subsurface layers. Without loss of generality, lunar subsurface structure is represented by a multi-layer model, with the total number of layers *n*. Each layer is characterized by its thickness and complex dielectric constant. Then, the received GPR echo from the base of the *m*-the layer can be calculated as

$$E_{r,m} = E_{inc} R_{m,m+1} \prod_{i=1}^{m} T_{i-1,i} T_{i,i-1} \exp\left(-2k_i'' \cdot d_i\right) \tag{1}$$

where E_{inc} is the strength of the incident radar wave, k_i is the complex wavenumber in layer *i*, d_i is the thickness of layer *i*, and $R_{i,j}$ and $T_{i,j}$ are the reflection and transmission coefficient from layer *i* to *j*, respectively. Since the size of buried rock is generally much smaller than the selected GPR wavelength, scattering from buried rocks in the subsurface is ignored in our current model. In our simulation, the transmitted wave is selected as differentiated Gaussian pulse.

Sinus Iridum region will be probably the first choice of the landing site for China's Chang-E 3 rover [9]. Figure 1a shows the surface topography of Sinum Iridum region, where the white line indicates an assumed GPR ground track for our simulation, and Figure 1b shows the FeO and TiO_2 abundances. Previous analyses show that the regolith thickness of this region is about 4-6 m [3,6]. Figure 1c shows an assumed four layer subsurface structure of this region. In our simulation, for the first two layers, the thicknesses were assumed to vary linearly from 2 to 6 m and from 4 to 12 m, from the 40 °N to

47 °N, and the thickness of the third layer varies randomly, with a mean depth of 82 m below the surface. The complex dielectric constant of each layer was calculated from [8], with the porosity of each layer of 0.58, 0.39 and 0.19, and the dielectric constant of the fourth layer was set equal to 10.0+i0.02.

Figure 1d shows the simulated GPR echoes at 450 MHz as a function of depth, where the real part of the dielectric constant was assumed to be 3.0 for the whole subsurface layer. It can be seen that radar echoes from the first and second layer are very clear. It is hard to see any reflected echoes from the third layer for latitude from 40 °N to 42.5 °N, because the thickness and ilmenite abundance of the third layer for this region are large.

If the radiometric calibration of GPR is good, surface echo strength can be used to estimate the real part of the dielectric constant for the first layer. Then using the time delay between the surface and the base of the first layer, thickness of the first layer can be estimated. Using the same method and the loss tangent that estimated from composition, the real part of the dielectric constant and thickness of the underlying layers could be estimated subsequently.

Conclusions: A ground penetrating radar with frequency at VHF and P band can penetrate lunar subsurface to a depth from several meters to hundred meters depending on the composition. Simulation results show that subsurface structure can be investigated from the GPR echoes, if the thickness and the dielectric loss of the subsurface are not too large. Information about the real part of the dielectric constant and layer thickness can be estimated if absolute calibration of GPR is good.

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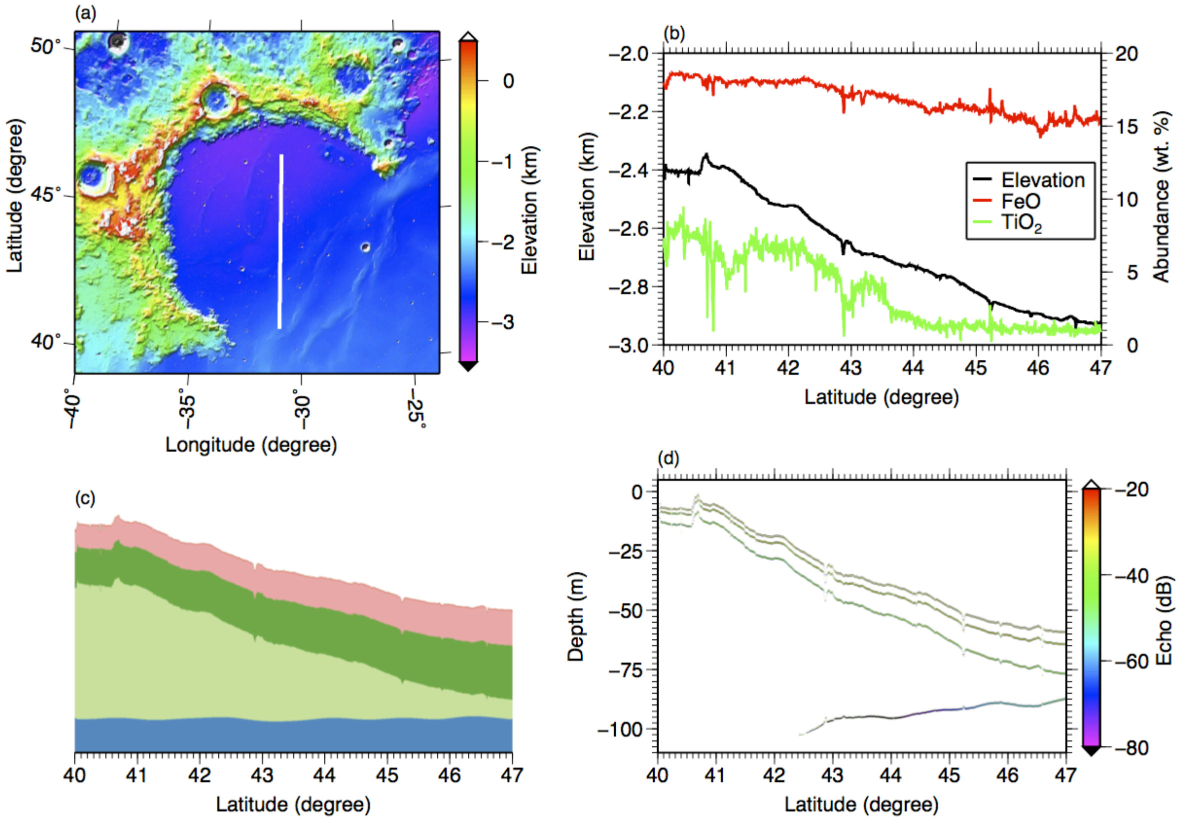

Figure 1. (a) Topography of Sinus Iridum regions, where the white line shows an assumed ground track for a rover deployed GPR. (b) FeO, TiO_2 abundnace and elevation for the white line (Longitude -31°W, Latitude 41-47°N). (c) An assumed four layer model of the subsurface for Sinus Iridum. (d) Simulated GPR echo strength for the subsurface, with a center frequency of 450 MHz.