Estimation of the Dielectric Characteristics of Lunar Subsurface Layers using the Kaguya Lunar Radar Sounder. Y. Cai[1,2] and J. Guo[2], [1] National Key Laboratory of Science and Technology on Remote Sensing Information and Imagery Analysis, Beijing Research Institute of Uranium Geology, Beijing, China (yzcai@csust.edu.cn), [2] Changsha University of Science and Technology, Hunan, China.

Introduction: The relative dielectric constant is important to characterize the lunar regolith, which is constrained by the bulk density, particle size, and chemical composition of lunar shallow surface [1]. The real part of dielectric constant of lunar rock samples is measured as between 4 and 10 in laboratory [2]. For igneous, sedimentary and clastic rocks, the loss tangent is generally very small. In order to study the dielectric properties of the lunar maria in a wide range, we used the data from the 5 MHz Lunar Radar Sounder (LRS) carried on SELENE to estimate the relative dielectric constant [3].

Our study can be roughly divided into five steps: (1) pre-processing, processing and imaging of LRS data; (2) detection of surface nadir and sub-surface structures in A-scope plots; (3) detection of surface nadir and sub-surface structures in in B-scan images; (4) influence of surface Fe and Ti content on sub-surface structure detection; (5) Spatial distribution and the relative dielectric constant estimation of subsurface boundary structures.

Data: Low-frequency electromagnetic waves can detect subsurface structures at a certain depth below the surface. The instrument used in this study is the 5 MHz Lunar Radar Sounder (LRS) on board the Luna Selene 1. The LRS instrument has a bandwidth of 2 MHz and achieves a detection resolution of 75 m in vacuum, and the transmitting antenna is a 30 m long dipole antenna [3].

The radar sounder data includes two parts: file header and data. The data part is stored in binary code, and the data include pulse observation time, time delay, longitude, latitude, altitude, and real and imaginary part values of the echo power. There are 1000 sets of real and imaginary data for the one sub-spacecraft observation along a satellite orbit, representing an increasing distance from the spacecraft and a depth direction interval of 25 m. The latitude of the sub-star increases along the direction of the spacecraft orbit, with each data spanning about 5 degrees in the latitude direction.

Method: *Detection of nadir echo and subsurface echoes from A-scope plots of LRS.* A-scope plots the echo power from depths of several km. Usually, the lunar surface echoes come from the most intense value of reflection echoes in A-scan plot. The subsurface echo is recognized as the second distinct peak value in A-scan plot, and the intensity difference between and surface echo needs to be discriminated by threshold value., which is set to be more than 4 dB in our study (Fig.1).

Detection of nadir echoes and subsurface echoes from B-scan images. B-scan images plot the received echo power as a function of depth and latitude, and then the results of the surface nadir echo and the subsurface echo identified in A-scope plot is superimposed (Fig.2). If the subsurface echoes from different time series in B-scan image are showed as a continuous line in similar depth, which implies that the continuous line should be the subsurface boundary interface. B-can images also could tell the start-point and endpoint of the subsurface boundary interface. In addition to the first subsurface layer below the surface, there are multiple layered structures below the surface in some lunar maria regions [4].

Estimation of the relative dielectric constant of subsurface layers. Based on surface/subsurface echo and apprant depth of subsurface layer detected in B-scan images, we estimate the the relative dielectric constant of subsurface material. Based on Fresnel's law, the relative dielectric constant can be estimated by subsurface attenuation and reflection coefficient of the medium [5].

P_0 is the incident power of LRS, and P_1, P_2, represent the reflected power from the surface and subsuface boundary contacts. The reflective coefficients form surface and subsurface boundary are R_{12} and R_{23}, and the apparent range and real range between surface and subsurface boundary are D and d respectively. Therefore,

$$P_1 = P_0 R_{12}^2$$

$$P_2 = P_0(1-R_{12}^2)e^{-2\alpha d} R_{23}^2 e^{-2\alpha d}(1-R_{12}^2) = P_0(1-R_{12}^2)^2 R_{23}^2 e^{-4\alpha d}$$

When P_0 and P_1 are both expressed with dB,

$$P_1 = 10\log(P_1/P_1) = 0$$

$$P_2 = 10(P_2/P_1) = 10\log\left[\frac{(1-R_{12}^2)^2}{R_{12}^2} R_{23}^2 e^{-4\alpha d}\right]$$

$$P_2 = 10\log\left[\frac{(1-R_{12}^2)^2}{R_{12}^2} R_{23}^2\right] + (-40\alpha d)\log e$$

We may approximate $\alpha \approx \frac{\pi\varepsilon''}{\lambda_0\sqrt{\varepsilon'}} = \frac{\pi\tan\delta\sqrt{\varepsilon'}}{\lambda_0}$, and real range $d = D/\sqrt{\varepsilon'}$, then the relationship between dB value of surface and subsurface echo and loss tangent and D is as follows

$$\tan\delta = \sqrt{\left\{2\left[\frac{\lambda_0}{8\pi D}\ln\left(\frac{P_{sur}}{P_{sub}}\right)\right]^2 + 1\right\}^2 - 1}$$

It is noticed that the application of the formula only applied to the surface and first subsurface boundary.

Results: As so far, for Mare Crisium, Mare Serenitatis, Mare Tranquillitatis and Mare Fecunditatis, the detection of subsurface structure and estimation of the loss tangent have been completed. Our results show that Mare Crisium and Serenitatis have 104 and 141 LRS data detected with subsurface layers (Fig.3). There is a strong correlation between the subsurface structure and titanium content in Mare Serenitatis only in the area where titanium content is relatively low (< 6 wt.%). The maximum apparent depth of subsurface layer in Mare Serenitatis can reach l3.5 km below the surface. The loss tangent results are shows in Table 1. We plan to compare the loss tangent estimated in this work with the results estimated form UVVIS data.

Table 1. Apparent depth of subsurface layers and the loss tangent estimated in this study.

Maria	apparent depth (m)	loss tangent
Mare Crisium	200–1925	0.015–0.06
Mare Serenitatis	225–575	0.016–0.058
Mare Tranquillitatis	375–2250	0.006–0.032
Mare Fecunditatis	775–3475	0.0018–0.0095

References: [1] Fa W. et al., (2012) *Icarus*, *218*, 771–787. [2] Carrier et al., (1991) *Lunar Source-Book: A User's Guide to the Moon,* 530–552. [3] Kobayashi T. et al. (2010) *GRSL*, *7,* 435–439. [4] Oshigami S. et al., (2014) *JGR*, *119*, 1037–1045. [5] Bando Y. et al., (2015) *Icarus*, *254*, 144–149.

Additional Information: This work is supported by Fund of National Key Laboratory of Science and Technology on Remote Sensing Information and imagery Analysis, Beijing Research Institute of Uranium Geology (Grant No. 6142A01210408).

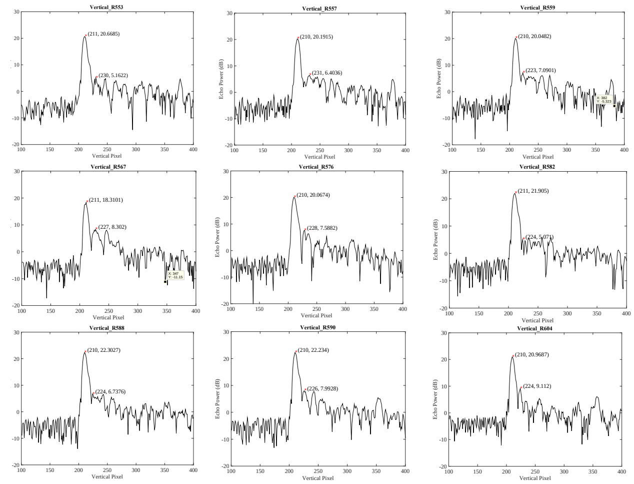

Fig.1. Nine A-scope plots from LRS data that show the surface nadir and subsurface echo.

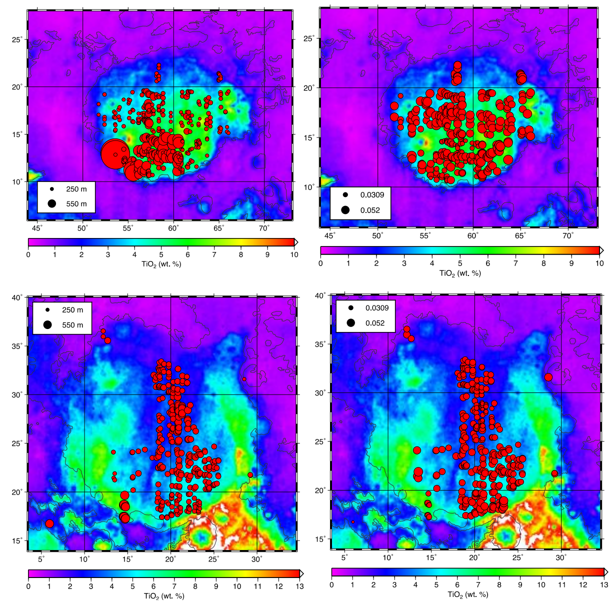

Fig.3. Apparent depth (left column) of subsurface layers and the loss tangent estimated in this study (right column) of subsurface layer in Mare Crisium (top) and Mare Serenitatis (bottom).

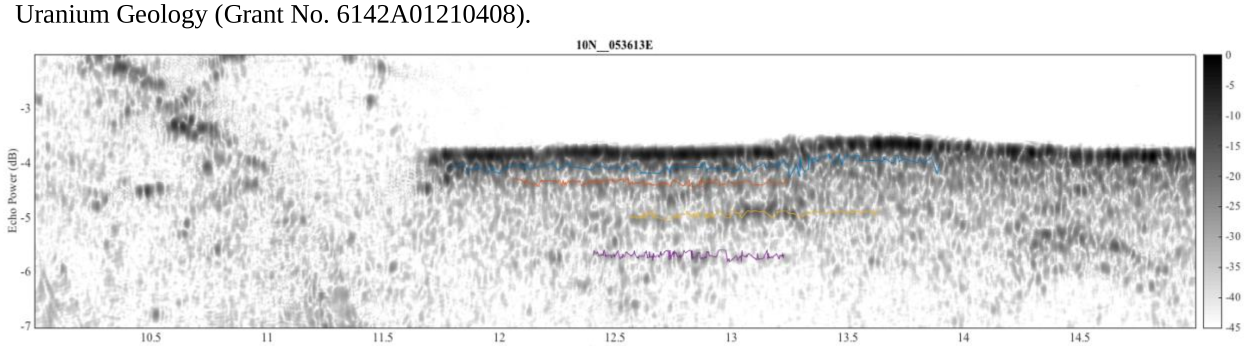

Fig.2. B-scan image that show multi-subsurface layers.