**A STUDY OF THE LUNAR SUBSURFACE ECHO INTENSITY FOR EVALUATION OF THE MAXIMUM DETECTION DEPTH OF THE KAGUYA LUNAR RADAR SOUNDER.**
A. Kumamoto[1], T. Ono[1], and T. Kobayashi[2], [1]Tohoku University (kumamoto@pparc.gp.tohoku.ac.jp), and [2]Korea Institute of Geoscience and Mineral Resources.

**Introduction:** Recent studies based on the subsurface radar sounding of the Moon by Kaguya Lunar Radar Sounder (LRS) have prominently shown that the radar sounder is a powerful tool for geological investigations of the planets and satellites [1-5]. On the other hand, we have also recognized several limitations and difficulties in the actual radar sounder observations. Radio wave attenuation in the surface material is one of those limitations in the lunar subsurface radar soundings. Based on the data obtained by Kaguya/LRS, it was reported that there were found inhomogeneity of the subsurface reflectors in the Oceanus Procellarum [4]. As for the inhomogeneity, it was also suggested that the abundance of the ilmenite such as FeO and $TiO_2$ affects the detectability of the subsurface echoes [5]. The loss tangent of the Apollo lunar samples was well investigated in the previous studies. They reported that the loss tangent of the lunar soils and rocks depends on their mass density and abundance of ilmenite as following regression equation:

$$\tan\delta = \{(0.00053 \pm 0.00056) + (0.00025 \pm 0.00009)C\}\rho \quad (1)$$

where $C$ is total abundance of FeO and $TiO_2$ in wt.%, and $\rho$ is mass density in g/cm$^3$ [6]. It is therefore inferred that rich ilmenite in the lunar surface material could cause the radio wave attenuation and degrade the detectability of the subsurface echoes and maximum detection depth of the radar sounder. The abundance of FeO and $TiO_2$ on the lunar surface can be measured by using Clementine UV-Visible image data [7-10] and Lunar Prospector (LP) Neutron and Gamma-Ray Spectrometer data [11-13]. In the present study, we performed estimation of the subsurface echo powers based on the reflection coefficient at the buried regolith layers and attenuation rate in the basalt lava flow layers between the buried regolith layers. Then we also estaimate the maximum detection depth of Kaguya/LRS.

**Estimation of Subsurface Echo Power:** We made the following assumptions: (i) The subsurface reflectors detected by LRS are buried regolith layers [1]. Their thickness is several meters, which is much less than LRS range resolution (75 m in vacuum). Their permittivity is ~4. (ii) The layers between the subsurface reflectors are basalt lava flow layers. Their thickness is several hundred meters, which can be determined by LRS. Their permittivity is ~6.25. The mass density is ~3 g/cm$^3$. (iii) The abundances of FeO and $TiO_2$ of the regolith layers and basalt layers are almost similar with those on the lunar surface, which can be derived from Clementine multiband image [9]. Based on the assumptions, we can calculate the reflectance at the buried regolith layers, and attenuation per meter in the basalt lava flow layers. Due to the interference between radio wave reflected at the upper and lower boundaries of the buried regolith layer, the total reflectance at the buried regolith layer depends on the thickness of the buried regolith layer. The reflectance is given by

$$E = R \cdot E_0 \left\{ \exp\left[ i\int_{-2s/c}^{t-2s/c} \omega(t')dt' \right] + \exp\left[ i\int_{-2\left(s+\sqrt{\varepsilon_{r,R}}d\right)/c}^{t-2\left(s+\sqrt{\varepsilon_{r,R}}d\right)/c} \omega(t')dt' \right] \right\} \quad (2)$$

where $R$ is reflectance between regolih and basalt rocks, $E_0$ is incident wave amplitude, $\omega(t)$ is angular frequency of radar pulse, $t$ is time, $s$ is light path from the spacecraft to the upper boundary of the regolith layer, $\varepsilon_{r,R}$ is the permittivity of the regolith, $d$ is regolith layer thickness, and $c$ is the speed of ligh. The subsurface echoes from the buried regolith layers with a thickness of 1 m is 20 dB weaker than the nadir surface echoes. The $\tan\delta$ in the nearside maria are estimated at 0.016 based on the FeO and $TiO_2$ map, which is much more than that used in the prelaunch estimations [14,15]. The relation between the attenuation rate and loss tangent is given by

$$\alpha = 0.091 f \sqrt{\varepsilon_{r,B}} \tan\delta \quad (3)$$

where $\alpha$ is attenuation rate in dB/m, $f$ is frequency in MHz, and $\varepsilon_{r,B}$ is the permittivity of the basalt rocks [5, 16]. The attenuation rate in the nearside maria is therefore 6 dB/km. Based on the calculated reflectance and attenuation rate, and noise level of Kaguya/LRS, which is 50 dB less than the nadir surface echo level, the maximum detection depth of Kaguya/LRS can be estimated by

$$D_{\max} = \frac{P_{sub} - P_{noise}}{\alpha} \qquad (4)$$

where $D_{\max}$ is maximum detection depth, $P_{\text{sub}}$ is subsurface echo level, and $P_{\text{noise}}$ is noise level of Kaguya/LRS. The map of Laguya/LRS maximum detection depth for the buried regolith layers with a thickness of 1 m is shown in Fig. 1. $D_{\max}$ in the nearside maria is estimated at 1 km.

**Discussion:** In the prelaunch studies [14, 15], maximum detection depth of the Kaguya/LRS was estimated to be 5 km because $\tan\delta = 0.006$ is assumed in them. That was, however, too small in the nearside maria. It was reported that Apollo Lunar Sounder Experiment (ALSE) detected the subsurface reflectors at depths of 1 km and 2 km in Mare Serenitatis [17]. However, Kaguya/LRS could not detect such deep reflectors in the same regions [1]. Because the transmitting power and dynamic range of ALSE are almost the same with those of Kaguya/LRS, the maximum detection depth of ALSE should be about 1 km. Therefore, it is quite unnatural that ALSE detected reflectors at a depth of 2 km. It was found in the present study that the subsurfcae echo power depends on the thickness of the buried regolith layers. The results will enable us to determin the regolith accumulation rate, the age of buried regolith layers, and the evolution of the volcanic activity in the lunar maria in future works.

**References:** [1] Ono, T. et al. (2009) *Science*, *323*, 909. [2] Kumamoto, A. et al. (2009) *Yuseijin*, *18*, 18-24. [3] Ono, T. et al. (2010) *Space Sci. Rev.*, *154*, 145-192, doi:10.1007/s11214-010-9673-8. [4] Oshigami, S. et al. (2009) *GRL*, *36*, L18202, doi:10.1029/2009GL039835. [5] Pommerol, A. et al. (2010) *GRL*, *37*, doi:10.1029/2009GL041681. [6] Olhoeft G. R. et al. (1975), *Earth Planet. Sci. Lett.*, *24*, 394-404. [7] Lucey, P. G. et al. (1995) *Science*, *268*, 1150-1153. [8] Lucey, P. G. et al. (1998). *JGR*, *103(E2)*, 3679-3700. [9] Lucey, P. G. et al. (2000) *JGR*, *105(E8)*, 20,297-20,305. [10] Wilcox, B. B. et al. (2005) *JGR*, *110*, E11001, doi:10.1029/2005JE002512. [11] Lawrence, D. J. et al. (1998) *Science*, *281*, 1484. [12] Elphic, R. C. et al. (2000) *JGR*, *105(E8)*, 20,333-20,345, [13] Lawrence, D. J. et al. (2002) *JGR*, *107(E12)*, 5130, doi:10.1029/2001JE001530. [14] Ono, T. et al. (2000) *Earth Planets Space*, *52*, 629-637. [15] Ono, T. et al. (2008) *Earth Planets Space*, *60*, 321-332. [16] Chyba, C. F. et al. (1998) *Icarus*, *134*, 292-302. [17] Peeples, W. J. et al. (1978) JGR, 83(B7), 3459-3468.

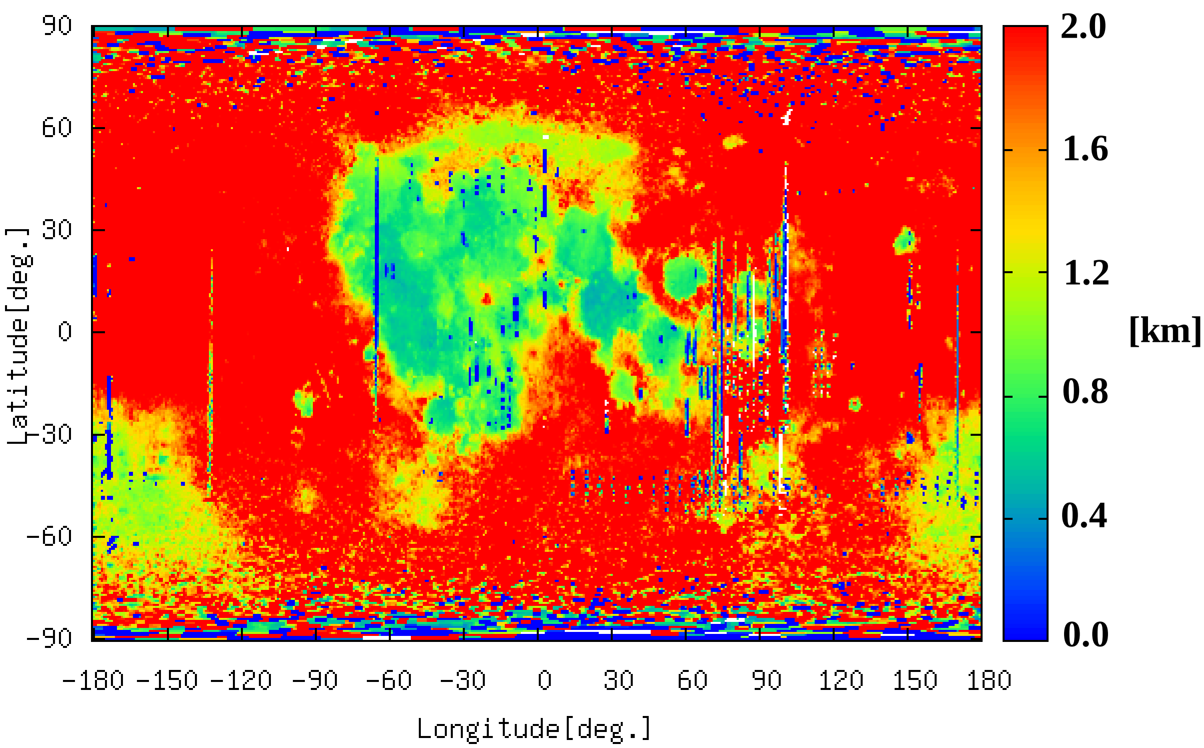


**Fig 1.** Map of Kaguya/LRS maximum detection depth for buried regolith layers with a thickness of 1 m. The maximum detection depth in the nearside maria is about 1km.