DERIVATION OF LUNAR SUBSURFACE LOSS TANGENT FROM SELENE LUNAR RADAR SOUNDER.
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Introduction: Loss tangent of the lunar uppermost layer up to depth of ~700 m has been estimated based on the SELENE (Kaguya) Lunar Radar Sounder (LRS) data. Loss tangent is dependent on the abundance of high conductivity material such as FeO and TiO_2. An empirical relation between loss tangent and total abundance of FeO and TiO_2 was obtained based on measurements of Apollo samples [1].

Loss tangent can be estimated from attenuation of electromagnetic pulse of the radar. It is however difficult to estimate attenuation simply from measured echo intensity because the reflectance at the subsurface reflectors could not be the same due to differences of the permittivity and roughness at the reflectors. Therefore, some studies proposed to use frequency dependence of the attenuation. Attenuation in high frequency range is larger than that in low frequency range. Subsurface loss tangent of the uppermost material in several areas of the Mars by splitting chirp signal into high- and low-frequency components using Mars Reconnaissance Orbiter (MRO) Shallow Radar (SHARAD) data [2]. Some studies proposed to use down shift of centroid frequency at which echo power can be equally divided [3, 4, 5]. They applied this method to the Earth's and Lunar GPR data.

Purpose of this study is to establish the estimation method of subsurface loss tangent by using SELENE LRS data. Subsurface ilmenite abundance can be derived from estimated subsurface loss tangent. The subsurface ilmenite abundance estimated from subsurface loss tangent was then compared with surface ilmenite abundance derived from SELENE multiband image data.

Method: We applied splitting chirp method to SELENE LRS data. In LRS onboard signal processing, the both low-frequency (4-5 MHz) and high-frequency (5-6 MHz) components of echo signals are converted into pulse-compressed signal in a frequency range less than 2 MHz. The pulse-compressed signal is sampled at 6.25 MHz and converted to 2048-point waveform data [6]. In order to divide the pulse-compressed waveform into low- and high-frequency components, we applied window functions with different starting time. For echoes with delay τ from sampling start, window function from τ to τ + 100 μs is applied to obtain low-frequency component, and that from τ + 100 μs to τ + 200 μs is applied to obtain high-frequency component. Using the echo power difference between low- and high frequency components, $\Delta P = P_L - P_H$, loss tangent can be estimated as

$$\tan\delta = \frac{\Delta P}{0.091\times\Delta f\times c\tau} = 0.037\frac{\Delta P[\mathrm{dB}]}{\tau[\mu\mathrm{s}]} \quad (1)$$

where Δf is frequency difference in MHz (1 MHz), and c is light speed in vacuum (3×10^8 m s^{-1}). The ratio ΔP / τ can be obtained by least square fitting. In order to avoid using ΔP derived from low-SNR P_L and P_H, the data with the highest 10% P_L and P_H are used in the analysis. Total abundance of FeO and TiO_2 can be derived from estimated subsurface loss tangent by

$$FeO[\mathrm{wt\%}]+TiO_2[\mathrm{wt\%}] = \frac{\tan\delta/\rho - 0.00053}{0.00025} \quad (2)$$

where ρ is mass density in g cm^{-3} (3 g cm^{-3}) [1].

Results: In the beginning, ΔP as a function of τ was derived from SELENE LRS data obtained in a 1°×1° area at (21°E, 23°N) in Mare Serenitatis as show in Fig. 1. The path is along longitude of 23°E, in which echoes from subsurface reflectors at depth of ~180 m are observed [7]. While ΔP is much deviated, we can confirm ΔP trend shows positive slope. By applying least square fitting, ΔP / τ was estimated to be 0.37 dB/μs. Using Equation 1, subsurface loss tangent was derived as 0.014. Using Equation 2, subsurface (FeO+ TiO_2) abundance was estimated to be 16 wt%.

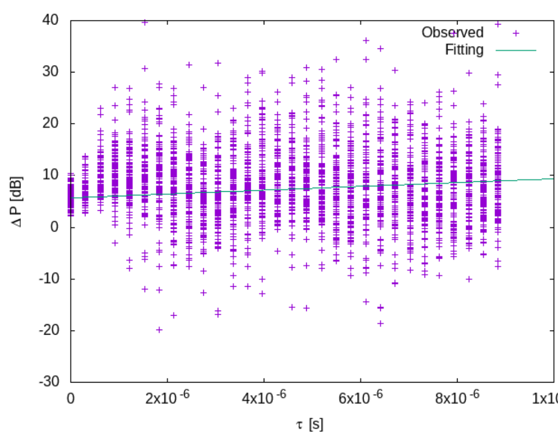

Fig. 1: ΔP as function of τ derived from SELENE LRS data obtained at (21°E, 23°N) in Mare Serenitatis

Next, subsurface loss tangent estimation was performed for SELENE LRS data obtained in wider area with longitude range from 5 to 30°E and latitude range from 25 to 40°N, which include the whole of Mare Serenitatis. Using Equation 2, subsurface (FeO+TiO_2)

abundance can be estimated from subsurface loss tangent. The subsurface ($FeO+TiO_2$) abundance estimated from SELENE LRS data was compared with surface FeO abundance estimated from SELENE Multiband Imager (MI) data [8] by applying Lemelin's method [9, 10], which was modified from Lucey's method [11]. The relation between surface FeO abundance and subsurface ($FeO+TiO_2$) abundance is shown in Fig. 2. While subsurface ($FeO+TiO_2$) abundance is much deviated, positive correlation between surface FeO and subsurface ($FeO+TiO_2$) abundance can be found.

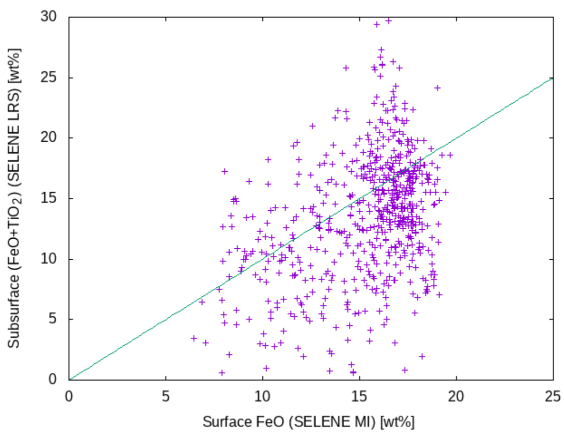

Fig. 2: Relation between surface FeO and subsurface ($FeO+TiO_2$) abundance in a area including the whole of Mare Serenitatis.

Discussion: Positive correlation between surface FeO and subsurface ($FeO+TiO_2$) abundance in Fig. 2 suggests that chirp-split method basically works well in application to SELENE LRS data. Large deviation of loss tangent and derived ($FeO+TiO_2$) abundance is from large deviation of ΔP, or P_L and P_H probably due to inclusion of off-nadir surface echoes.

Even including the TiO_2 abundance, the estimated subsurface ($FeO+TiO_2$) abundance is a little less than surface FeO abundance. A possible explanation is that subsurface FeO abundance is actually less than surface FeO abundance. It was suggested that lava flow flux suddenly decrease at ~3.0 Ga, and TiO_2 abundance in large lava flow flux is lower than in low lava flow flux [12]. If it can be applicable also for FeO, FeO abundance in subsurface old lave layers could be less than that in surface new lava layers.

Summary: Loss tangent of the lunar uppermost layer up to depth of ~700 m has been estimated by applying chirp-split method to the LRS data. In a path along longitude of 23°E above Mare Serenitatis, in which subsurface echoes are observed, we could estimate subsurface loss tangent as 0.014 and subsurface ($FeO+TiO_2$) abundance as 16 wt%. We also applied the subsurface loss tangent estimation method to wider area including the whole of Mare Serenitatis. Subsurface ($FeO+TiO_2$) abundance derived from subsurface loss tangent shows positive correlation with surface FeO abundance derived from SELENE MI data. The estimated subsurface ($FeO+TiO_2$) abundance is a little less than the surface FeO abundance, which would make suggestions on the evolution of the ilmenite abundance in lava flow in the lunar thermal history.

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