Development of the detection algorithm and its demonstration results for lunar lava tubes by Lunar Radar Sounder (LRS) onboard SELENE (Kaguya)

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Lunar lava tubes preserve human life and the internal environment from external factors which are meteorites impacts, high-energy UV radiation, and extreme temperature variations [e.g., Oberbeck et al., 1969]. Therefore, intact lava tubes on the Moon are important to understand Moon's volcanism and eruptive lava characteristics and also construct future lunar bases. Recently, Terrain Camera (TC) onboard SELENE (Kaguya) discovered some skylights that were thought to be formed over the lava tube [Haruyama et al., 2009]. In addition, the high-resolution imaging by LRO showed the detailed structure of those skylights and the existence of horizontal cavities extending laterally from the skylight [Robinson et al., 2012]. Later, the depressions and the second echo peaks of radar reflection intensity by Lunar Radar Sounder (LRS) onboard SELENE (Kaguya) were found on the Marius Hills region [Kaku et al., 2017]. Because these radar signals are consistent with mass deficits area by GRAIL [Chappaz et al., 2017], they strongly support intact lava tubes on the Moon. Although lava tubes have not been discovered except for the Marius Hills region by LRS at present, it may be possible that intact lava tubes remain undiscovered without meeting the detection criteria of the previous research. The detection thresholds used in previous research are not based on physical theory but are empirically determined. Therefore, it is necessary to verify the detection method by a physical simulation. In addition, since surface scattering noise exists in actual LRS data, it is necessary to properly remove them for more accurate lava tube detection [e.g., Kobayashi et al., 2020].
The purpose of this study is to construct a new detection algorithm for the LRS data that enables the mapping of global lunar lava tubes. To accurately evaluate the radar reflection intensity from the lava tube, we investigate radar patterns for cases where a lava tube exists underground by the Finite Difference Time Domain (FDTD) method, which is one of the electromagnetic propagation simulations. Here, lava tube shape is assumed semi-elliptical cross-section. As a result, we showed a lava tube at a depth of 150 m or more has triple echoes from the ground surface, roof, and floor. On the other hand, for lava tubes shallower than 150 m, echoes from the ground surface and roof overlap. Consequently, we found the ground surface reflection intensity vibrates against that of a case with nothing underground.
In addition, we create the surface scattering simulation code using the Kirchhoff approximation to evaluate surface scatter noise. Here, the electromagnetic field is calculated by inputting the Digital Terrain Model (DTM) calculated by the TC camera images. Since the result obtained by this simulation only include reflections from the ground surface, only echoes from the subsurface structures can be extracted by taking the difference between the result and the actual LRS data. Finally, we successed to construct the new detection algorithm by detecting the echo pattern obtained by FDTD from the LRS data with the surface noise removed.
In this presentation, we also report the results of lava tube detection for the Marius Hills region where the lava tube has been discovered so far and the Rima Mairan region where the large mass defect is confirmed by GRAIL observation. In this way, we plan to discuss the importance of lava tube exploration and subsurface structure exploration for planets and satellites in the solar system.

Keywords: Lava tube, Lunar Radar Sounder(LRS), FDTD, Moon