EXPLORING RESOURCES ON THE MOON: TSUKIMI MISSION AND ASSOCIATED ACTIVITIES

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Introduction: NASA's plans for continued exploration and activities on the Moon include extended human missions and expanded robotic activities [1]. The presumed availability of volatiles on the Moon is one of the most important issues because it could affect the approach to near-term operations. If there is a valuable amount of water in an easy-to-use form, such as absorbed or cold-trapped ice [2-5], lunar activities could be largely supported by lunar materials. If not, lunar materials are still quite useful, while in terms of volatiles, sources other than the Moon may be the primary targets. Clear evidence of volatiles would be obtained by direct drilling by PRIME-1, VIPER [6], and LUPEX missions [7]. In this presentation, we will discuss a new Japanese science mission related to space resources and its potential role in this aspect and its associated activities.

TSUKIMI mission: TSUKIMI stands for Lunar Terahertz Surveyor for Kilometer-scale MappIng. It is a new Japanese lunar mission scheduled to be launched in 2026 supported by Ministry of Internal Affairs and Communications, JAPAN, and JAXA.

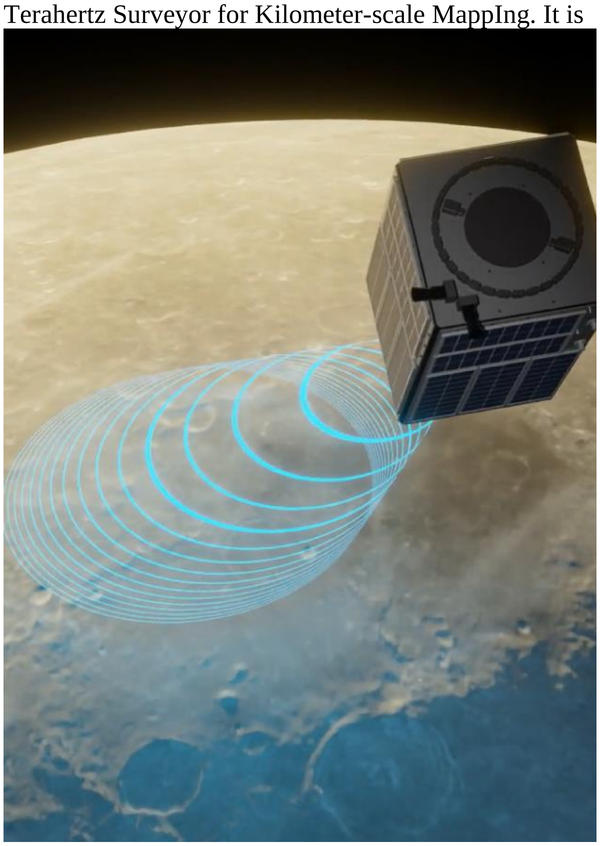

Fig. 1. Conceptual image of the TSUKIMI mission.

The mission will focus on the lunar surface down to 20-30 cm, because the lunar surface is the most accessible part of the Moon and therefore identifying its conditions could be useful. For this reason, we have chosen two frequencies, such as 280 GHz and 490 GHz. We will observe the polarization ratio of the brightness temperature in the two frequency ranges to derive the ABP, the apparent bulk permittivity, which is sensitive to the bulk density and the volatile or metal content. The polar orbit of TSUKIMI will allow repeated observations of polar regions, and we will measure the brightness temperature of the same regions several times to obtain the averaged value of the thermal diffusivities of very shallow depths of the lunar soil within the FOV, which is less than 1 km in diameter.

The TSUKIMI science team is closely working with the LUPEX science team because the TSUKIMI data, especially the ABP, would greatly benefit from lunar surface observations. In particular, lander missions with drilling experiments such as PRIME-1, VIPER [6], and LUPEX [7] will provide important, highly accurate, and definitive results on the vertical structure of the lunar soil. The TSUKIMI observation will observe a wide area of the Moon, which will be useful to extend the views obtained by the lunar landing missions in the horizontal direction.

The TSUKIMI observations will also be compared with previous microwave measurements from the Mini-RF [8], Mini-SAR [9], and MRM [10] observations and the Diviner brightness temperature observations [11], which are obtained using a similar approach but at different depths. Since the lunar thermal diurnal skin depth is ~5 cm [12], these observations will be complementary to understand the conditions of the uppermost portion of the lunar regolith, such as its packing density and particle size-frequency distributions.

Lunar simulants and permittivity: We note that an accurate understanding of the permittivity of the lunar soil will be essential for the analysis of electromagnetic observations, including the TSUKIMI, Mini-RF, Mini-SAR, and GPR observations. For this reason, we develop various types of lunar simulants using basalt, anorthosite, gabbro, dunite, and ilumenite to match the elemental compositions by orbital observations [13] and systematically measure the permittivity in frequencies from VHF to Terahertz [14]. Interestingly, we find that the temperature dependence of the permittivity exists and differs between ice and rock [14], suggesting that permittivity measurements at different temperature conditions may be critical to identify ice. Also, the dependence is likely to exist in the frequency from VHF to sub-terahertz, so TSUKIMI's observations in terahertz have important advantage of not being affected by this dependence.

Lunar Dielectric Analyzer, LDA: The permittivity of the lunar regolith has never been measured on the lunar surface (except by the Chang'E-5 LRPR team, who made indirect measurements on the surface [15]). Therefore, we are developing the LDA, Lunar Dielectric Analyzer, for a simple and accurate measurement of the dielectric constant of the lunar surface. The development of the LDA is independent of the TSUKIMI mission and is funded separately by JAXA. The TRL of LDA is currently 6.

LDA measures the dielectric constants of the top 1cm, 25cm, 30cm, 40cm, 50cm and 1m of the lunar surface immediately below the installation location. LDA has the following three objectives:

(1) Obtain the first ground truth value of permittivity: LDA can provide the first ground truth value of the permittivity of the lunar surface. The in-situ measurement of this value is especially important for shallow depths, because a) previous permittivity analyses of return samples [16] are not performed with the theoretically suggested large porosity variations at shallow depths, because these cannot be easily reproduced under terrestrial gravity; b) the permittivity at such shallow depths is particularly important for the analysis of radar instruments in the UHF bands (such as Mini-RF, Mini-SAR, and GPR); and c) previous remote sensing observations, such as MRM and Mini-RF, provide estimates of permittivity with strongly model-dependent values [17-19], so calibration with ground-truth data is essential. Once calibrated, the chemistry and packing density of the regolith can be estimated using previous radar data.

(2) Determine the soil density profile of top 1m: LDA measures the dielectric constant of the lunar surface at different depths down to 1m without digging or coring, which allows us to see the density variations at different depths undisturbed for the first time (the dielectric constant is mainly controlled by the density when the soil chemistry is unchanged). A large density variation is expected in the shallow subsurface, but it has never been measured due to the difficulty of measuring without disturbing the original conditions. We note that the vertical density distribution is an important key parameter to discuss possible thermal conditions (and thus, volatile distributions) in depth [20].

(3) Detect subsurface ice if present: LDA can detect subsurface ice by using small changes in the dielectric constant at different temperatures, since it depends on temperature and the dependence is different for rock and ice [14]. LDA is designed to continuously monitor subsurface conditions for more than 50 hours on the Moon to observe the changes that occur under different temperature conditions. If LDA can monitor the dielectric constant under different illumination conditions (sunlight and shadow), where dramatic temperature changes are expected, LDA may be able to detect the formation of thin frost or the accumulation/migration of subsurface ice, as suggested by Schorghofer and Ahronson (2014) [21] and Reiss et al. (2021) [22]. LDA can, thus, monitor the soil conditions as well; if we install the LDA inside a sample container for the moon or asteroid, we may identify slight migration of volatile when the container is heated.

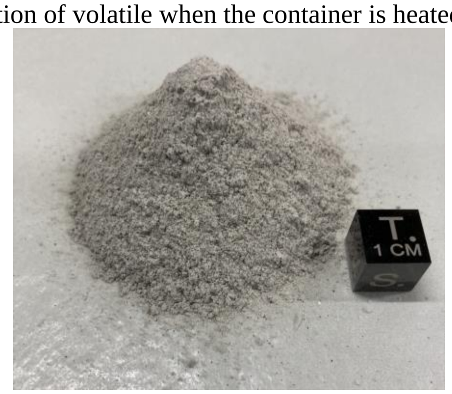

Fig. 2. Lunar highland simulant developed by U Tokyo

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