DETECTION OF LUNAR LAVA TUBES BY LUNAR RADAR SOUNDER ONBOARD SELENE (KAGUYA). J. Haruyama[1], T. Kaku[1,2], R. Shinoda[1,2], W. Miyake[2], A. Kumamoto[3], K. Ishiyama[1], T. Nishibori[1], K. Yamamoto[1], K. Kurosawa[4], A.I. Suzuki[1], S.T. Crites[1], T. Michikami[5], Y. Yokota[6], R. Sood[7], H. J. Melosh[7,8], L. Chappaz, K.C. Howell. [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan), [2]Engineering Department, Tokai University, [3]Science Department, Tohoku University, [4]Planetary Exploration Research Center, Chiba Institute of Technology, [5]Faculty of Engineering, Kindai University, [6]Faculty of Science, Kochi University, [7]School of Aeronautics and Astronautics, Purdue University, [8]Earth, Atmospheric and Planetary Science, Purdue University . E-Mail:haruyama.junichi_at_jaxa.jp (change "_at_" to @).

Introduction: In 2009, three huge pits were discovered on the Moon in image data acquired by the SELENE Terrain Camera. Their diameters and depths are several tens of meters or more.[1-3] They are possible skylight holes opening on large subsurface caverns such as lava tubes, [1] by analogy with similar pits found on Mars.[4] This possibility was enhanced significantly by LRO oblique observations; large openings were observed horizontally at the floors of the pits.[5] Robinson et al. (2012)[5] claim at least two possibilities for the large caverns associated with the skylight holes: a lava tube or a magma chamber. Lava tubes are normally elongated in the horizontal direction. In contrast, magma chambers may not have large horizontal extensions but instead may have drops like a sink around their inner walls as illustrated by Robinson et al. (2012).[5] Lunar caverns are protected from radiation, micrometeorites, and extreme temperatures, and thus are expected to be shelters in which humans will construct lunar bases. Lava tubes are likely more appropriate for lunar base construction than magma chambers. It is thus significant to investigate whether a lunar subsurface cavern is a lava tube or a magma chamber.

We analyze radar echo data acquired by the Lunar Radar Sounder (LRS) onboard SELENE (Kaguya) to determine whether there is any suggestion of the existence of elongated lava tubes along rille-A named by Greeley (1971).[6] The Marius Hills skylight Hole (MHH) is on the rille.

Lunar Radar Sounder (LRS) Data: The LRS transmits radar chirp pulses sweeping from 4 to 6 MH in 200 μsec, with an interval of 50msec corresponding to about 75m on the ground at the SELENE nominal altitude of 100 km.[7,8] The radiation power of LRS is 800 W to detect subsurface boundaries a few kilometers in depth. We use a product set of LRS echo data that has an improved signal-to-noise ratio by synthetic aperture radar (SAR) processing[9] with a synthetic aperture of 5 km. The data set is available via the JAXA/SELENE (Kaguya) data archive.[10]

Results: Figure 1 shows an A-scan diagram (powers of received echo vs elevation of subsurface reflecting the echo). The echo power was normalized to be zero dB for a standard surface echo level, and to be 0 km in elevation for the mean radius of 1737.4 km. The elevations that correspond to depths are calculated assuming the dielectric constant (ε) of the subsurface material. Here, the ε is temporarily set to be 1 that is the value in vacuum; the true depth should be shallower. The echo powers in Fig. 1 monotonically decrease with depth to the noise level, which means there is no subsurface clear boundary intensely reflecting the radar echo there.

Two large echo peaks were seen in the A-scan diagram (Fig.2) acquired at location "a" (about 1.2 km east and 0.3 km south from MHH). The largest echo is reflected from the ground surface. The second largest echo is from a subsurface boundary located at around -1500 m in elevation that is about 225 m in depth from the ground surface (for $\varepsilon = 1$). There is an abrupt echo power drop between the first and the second largest echo returns.

Figure 3 is a B-scan diagram that shows echo intensities expressed by a gray color scale in a plane where the x-axis is the SELENE flight track along a meridian and y-axis is elevation. Location (a) is indicated by an arrow in Fig. 3. The abrupt echo drop in Fig. 2 is expressed by the whitest spot at -1500 m in elevation. We note that the spot seems to be a cap of a parabolic pattern that is formed by white or whiter spots (low reflection echo power). There is no surface morphologic feature such as a large crater that could have caused the parabolic pattern. Therefore, there likely exists a subsurface media causing almost zero radar reflection that

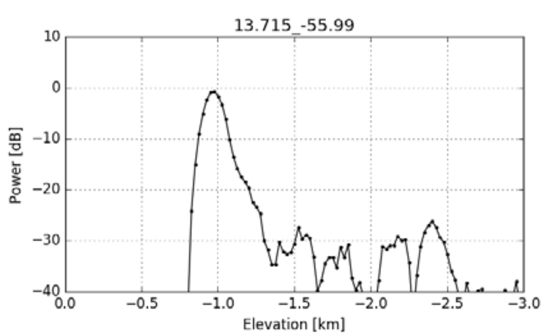

Fig. 1. A typical A-scan diagram of lunar radar sounder (LRS). The largest echo is from the ground surface. There seems to be few clear subsurface boundaries.

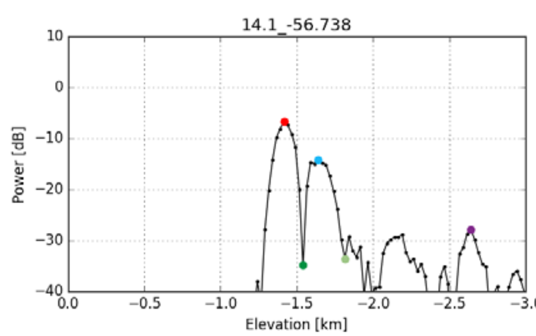

Fig. 2. A-scan diagram of location (a) in Fig. 4, close to MHH. A second strong echo can be seen.

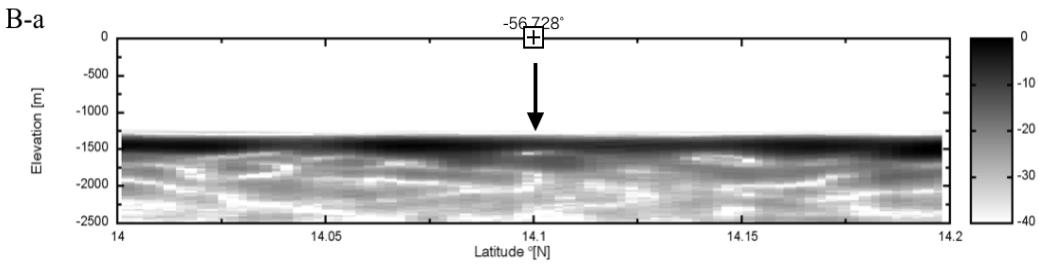

Fig. 3. B-scan diagram. Arrow indicates location (a) in Fig. 4. There is a large echo drop at location (a) expressed as a white spot at -1500m.

is a bulk of very dense rock or a large void.

Similar echo patterns were identified at some locations, westward of MHH (e.g. locations b, c, d, and e in Fig. 4) (Fig. 5).We note that location (b) is on rille-A, and that location (d) is near a subsided feature that seems to be a part of a collapsed lava tube.

Discussion and Conclusion: Recently Sood et al. (2015)[11] found gravity anomaly distributions suggesting the existence of subsurface empty spaces on the Moon based on GRAIL data, some of which may be intact lava tubes. Figure 4 is from their work for a region around MHH; the empty space candidates inferred from Bouger gravity anomalies are redder colors. There is a lava tube candidate that is a redder extension from near MHH in Fig. 4. Locations (a) to (d) are apparently on the extension. In contrast, location (e) seems to be misaligned from extension features (a) to (d). It may be regarded as a part of another subsurface lava tube.

The depths of void space candidates at locations (a) to (e) are nearly 120 m, assuming $\varepsilon = 4$ for the subsurface materials over the void. On the other hand, the floor depth of MHH is nearly 50 m based on LRO NAC data, [1][4][12] and overhangs are 30 to 40 m, shallower than inferred from LRS data. This may be explained as follows: 1) A micrometeorite impacted a lava tube. 2) The roof of the lava tube was damaged and totally comminuted in a moment. 3) The damaged fine materials of the roof dropped onto the floor of the tube. This process is supported by our computer simulations by using the iSALE shock physics code [e.g., 13].

In conclusion, it is strongly suggested that an intact lava tube at a depth extends a few tens of kilometers westward from MHH along rille-A, based on SELENE Lunar Radar Sounder echo data that is consistent with the results from GRAIL data analysis.[11]

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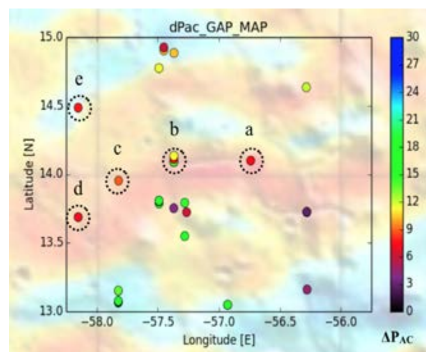

Fig. 4 Locations (a) to (e) where a large second peak of radar echo is found in A-scan diagrams. Back-ground is Bouger gravity anomaly; these likely are subsurface void candidates (expressed by redder colors). Location (a) is about 1.2 km east and 0.3 km south from the Marius Hills skylight Hole (MHH).

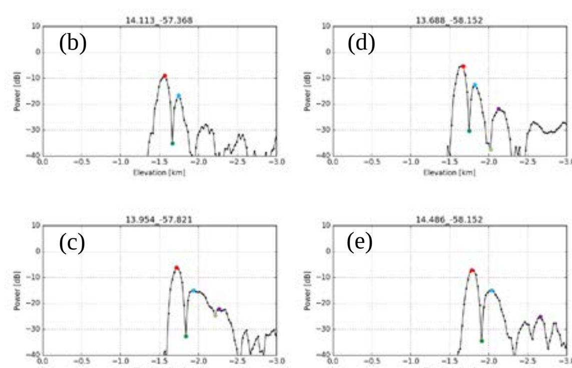

Fig. 5 A- scan diagrams of location (b) to (e).