

**SURFACE CLUTTER SIMULATIONS AND SUPER RESOLUTION PROCESSING OF THE SELENE (KAGUYA) LUNAR RADAR SOUNDER DATA.** V. Poggiali<sup>1</sup>, A. G. Hayes<sup>1</sup>, D. E. Lalich, J. M. Soderblom<sup>2</sup> and M. C. Raguso<sup>3</sup>, <sup>1</sup>CCAPS, Cornell University, Ithaca, NY, USA (vpoggiali@astro.cornell.edu), <sup>2</sup>EAPS, MIT, Cambridge, MA, USA, <sup>3</sup>JPL, NASA, Pasadena, CA, USA.

**Introduction:** Japan's first exploration mission to the Moon, the 2007 KAGUYA SELEnological and ENgineering Explorer (SELENE), was equipped with a 60 m wavelength Lunar Radar Sounder (LRS) [1]. This instrument successfully probed the Moon's deep subsurface (>1 km). Detailed interpretation of the return waveforms, however, are challenging in the absence of a rigorous surface clutter analysis. Similar to what happened with ALSE, it is difficult to distinguish real subsurface echoes from synchronized returns received from surface features ("clutter") away from and approximately parallel to the spacecraft ground track.

Accordingly, we have developed and implemented an EM wave propagation simulator to identify clutter in LRS data and have used it in combination with an algorithm of range resolution enhancement. The resulting reduced data products are enlarging the number of regions where the inversion of radar echoes for the estimation of subsurface dielectric properties can be safely performed or sensibly improved.

**Methods and techniques:** The LRS wave propagation simulator incorporates topography from the LRO Lunar Orbiter Laser Altimeter (LOLA) data grided at 512 pixel-per-degree. Our simulator uses elevation data to create a square and planar facet-based model of the surface with a scale of ~60-m/pixel both in latitude

and longitude. Each resolution cell is represented by a rectangular area with along-track dimension equal to the LRS SAR resolution cell and a cross-track dimension of ~100 km. This tool enables a straightforward distinction between real subsurface echoes and off-nadir returns from surface features, like the mare's scarps and ridges, both arriving at greater delay than the nadir surface echo. Figure 1 shows an example of a LRS radargram with its associated cluttergram. An ~300 m high ridge, barely visible in the optic images acquired by the SELENE Terrain Camera (TC), generates reflections in the radargram that correspond to synchronized recognizable reflectors in the cluttergram, thus revealing that they originate from surface features. It is worth to note that this clutter simulator is also able to show surface locations from which the radar returns originate or produce cluttergrams accounting only for the topography to the left and right side of the spacecraft. By comparing the radargrams and the simulated cluttergrams, we can perform a detailed analysis over regions of interest, e.g., candidate subsurface reflections that have been identified but not validated against the presence of rugged topography or where significant mass deficits have been identified within the high-resolution GRAIL gravity field determination [2].

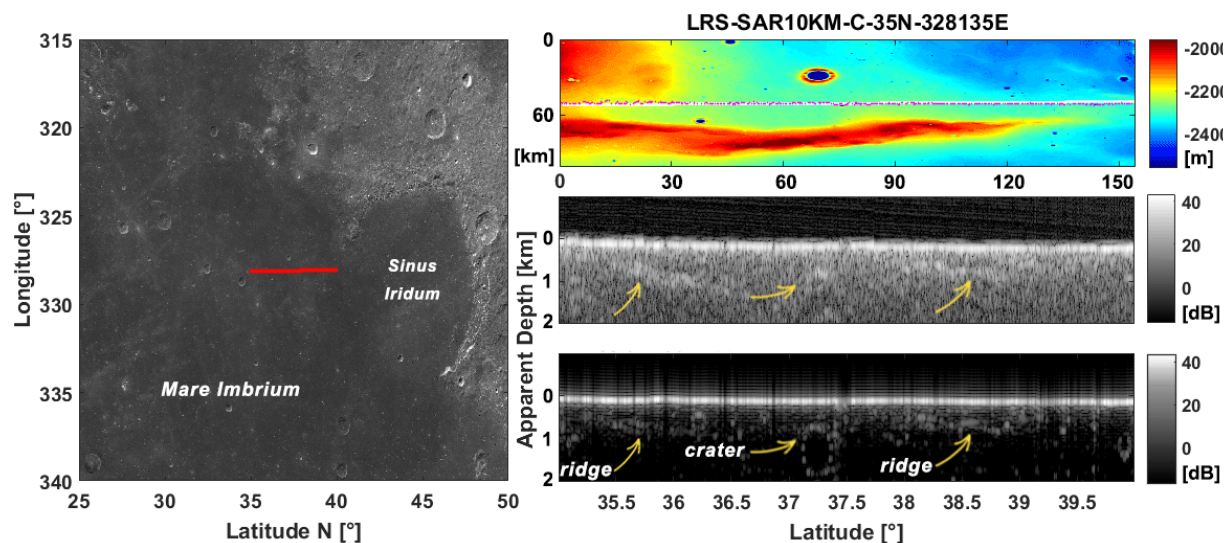


Figure 1: Long ridges and scarps generate lateral clutter that appear in radargrams as long linear structures like those generated by subsurface layers. In order to enhance the presence of the faintest lateral clutter and produce a better interpretation of the real data, no noise is added to the simulated cluttergram. More than perfectly reproduce LRS radargrams, our simulations want to be a support for distinguishing lateral surface clutter from actual subsurface reflectors. Pink dots close the white satellite ground track in the upper right panel indicate first-return locations.

The limited 75 m range resolution in free space of LRS can make the description of small-scale features, like lava tubes complexes, a prohibitive task. However, the use of appropriate spectral analysis algorithms allows an extension of the radar bandwidth over the conventional Rayleigh's limit. Autoregressive (AR) based spectral estimation techniques can be used to model and extrapolate the scattering field data beyond the measured range. We implemented Burg's Maximum Entropy Method (MEM), for its better stability and error control, and improved performance in low SNR regimes [3]. Our preliminary results show that the extrapolation of the received LRS signal can produce an improvement in the range resolution by up to a factor of 3. This technique has already been applied to several radar sounders on Mars [4, 5] and Titan [6]. In Figure 2 we show an example of application on the LRS.

**Future Work:** After the clutter simulator confirms the sub surficial nature of a reflection, bandwidth extrapolation enables better determination of its depth and, often, can reveal existence of other previously unresolved reflectors. Such reflectors can typically only be inferred by the slight skewness of the relative original waveforms. Using the clutter simulator and bandwidth extrapolation described herein, we plan to survey LRS data for lunar lava tube complexes.

The survey will consist of two tasks. First, we will re-analyze previously published returns over potential lava tube complexes. Second, we will survey the dataset for as of yet undiscovered lava tube complexes by investigating areas identified as having mass deficits, consistent with km-scale open caverns in the GRAIL

dataset [2]. We will also consider locations where skylights have been observed in SELENE TC [7] and LRO Narrow Angle Camera (NAC) [8, 9].

Observations of candidate lava tubes by the SELENE LRS display a distinctive response: a decrease in returned power followed by a large second echo that is consistent with a return from a subterranean cavity [9]. Once identified, we will characterize these features and determine their depth below the mare surface. We will implement standard radar data inversion techniques that use simulations to identify best fit values for subsurface layers permittivity through least squares minimization of the observed versus simulated waveforms and determination of their associated error distributions by adopting a Monte Carlo approach, similar to what we have previously done for studying Titan's seafloors [10, 11].

**References:** [1] Ono T. et al. (2010) Space Sci Rev 154(1–4), 145–192. [2] Chappaz L. et al. (2017) Geophys. Res. Lett., 44, 105–112. [3] Cuomo K. M. (1992) Lincoln Laboratory, MIT, Project Report CJP-60, Rev. 1. [4] Raguso M.C. et al. (2018) 26th EUSIPCO, 1212–1216. [5] Raguso M.C. et al. (2018) 5th IEEE MetroAeroSpace, 242–246. [6] Mastrogiuseppe et al. (2014) Geophysical Research Letters, 41, 1432–1437. [7] Haruyama, J., et al. (2009) Geophys. Res. Lett., 36, L21206. [8] Robinson M. S. et al. (2012) Planet. and Space Science, 69, 1, 18–27. [9] Kaku T. et al. (2017) Geoph Res Lett, 44, 10, 155–10,161 [10] Mastrogiuseppe M et al. (2016) IEEE TGRS, 54, 5646–5656. [11] Poggiali V. et al. (2020) Journal of Geoph. Research: Planets, 125. [12] Hongo et al. (2020) Earth, Planets and Space, 72:137.

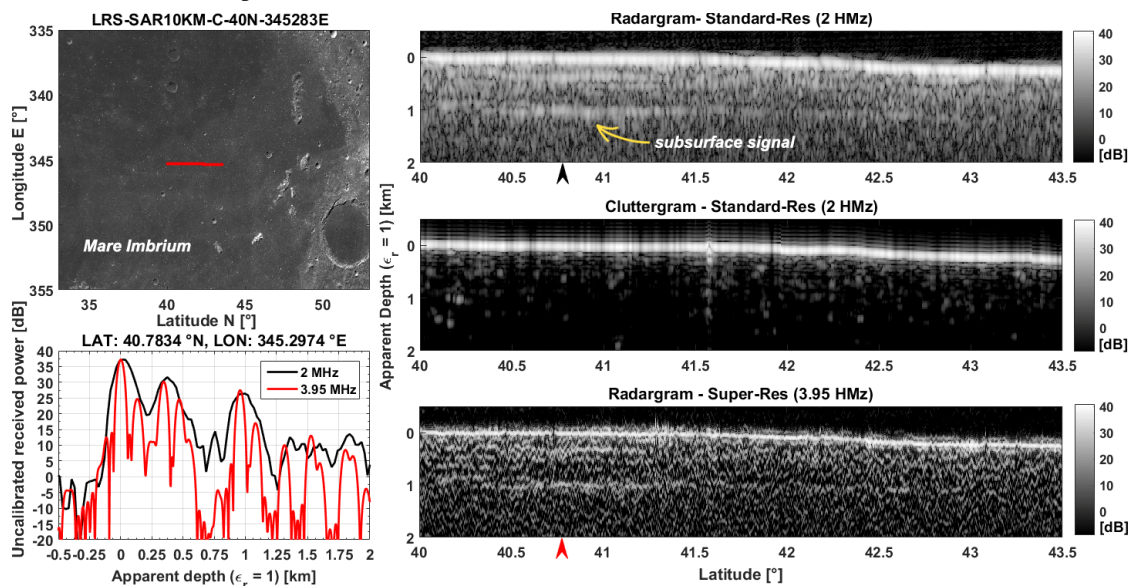


Figure 2: The absence of surface clutter in the cluttergram shown here (middle-right) confirms that the signals found in its associated LRS radargram (upper-right) acquired over the Mare Imbrium are actual subsurface reflectors, as hypothesized by Hongo et al. [12]. Here, the bandwidth of LRS has been almost doubled and one of the enhanced echoes (red arrow) has been plotted (lower-left) for comparison with the standard processed waveform.