RADAR MAPPING ON THE MOON: ADDING THE THIRD DIMENSION TO LUNAR PROSPECTING.

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Introduction: Today is an exciting phase of exploration of the Moon with many countries and companies directly involved in instrument design, mission planning, test flights, and executed missions. Moreover, the first commercial lunar prospecting mission – Oasis 1, the first step of Project Oasis being jointly developed by Luxembourg's national space agency and Blu Origin's Space Resources Center of Excellence. Critical – has been announced. Critical to successful operations on the Moon are adequate site characterization not just of topography but of geology and resources.

Higher resolution mapping of surface characteristics will be required for considering the highest priority landing sites that can potentially evolve to resource extraction location(s), and selection for moon base(s) [1]. Site characterization needs are beyond surface geology but extend to understanding the subsurface including depth to base of regolith, presence of impact or volcanic units, history of impacts affecting a site, and opportunities for in site resources-including critically water ice. Both the Lunar Roadmap and Moon to Mars philosophy are dependent on stable human presence on the Moon which requires resources and in particular water. Additionally, there are incredible opportunities to understand the geologic history of the Moon, advance technical capabilities, and solve new engineering challenges during the search for resources required for human operations.

Here we make the case for two key surveying technologies. First, lunar prospecting with an orbital SmallSat mission that overcomes existing challenges in guidance, control, and navigation and includes paired high-frequency radar sounder and neutron spectrometer to characterize the upper meters to 10s of meters of the Lunar subsurface. Second, a rover-based low size, weight, and power (SWaP) ground penetrating radar (GPR) system for precise local mapping at a landing site both with the potential for higher frequencies and clear opportunities for denser line spacing or even 3D data acquisition.

Mapping Ice: There is evidence for water's existence as ice buried within the lunar regolith [2-4], but large uncertainties exist in its spatial distribution, depth, form, and quantity (Figure 1) [5]. Evidence of water ice in 1-3 m depths has been previously realized but substantially more water ice and other potential forms of ice could be present at deeper depths. Due to high SWaP and resolution limitations, existing sensors used for sub-surface water detection radars leave the zone of ice potential at ~1-10 m depths unexplored.

Technical Challenge 1: SmallSat operations capable of achieving lunar global orbits and especially any low lunar orbits require advanced, accurate, robust, and compute efficient guidance and control algorithms consistent with SWaP limitations. High fidelity gravity models allow for orbital designs at a range of altitudes however perturbations due to mascons present a clear challenge. Any guidance and navigation control system for an autonomous SmallSat must be computationally efficient and capable of long-horizon planning while carefully accounting for mascons, computation, and communication limitations. Challenges also exist in consistent navigational and timing data due to weak GNSS signals from Earth-based satellites or ground tracking via

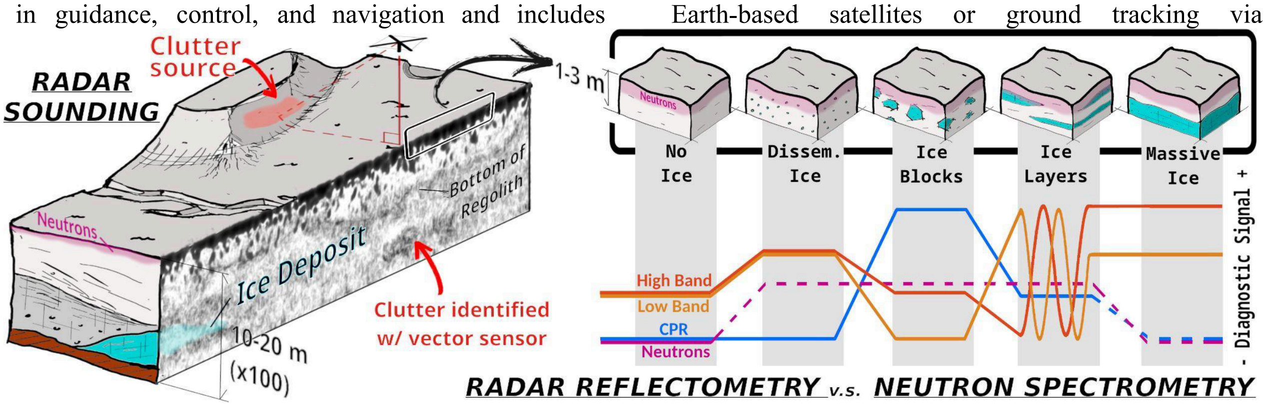

Figure 1. *Conceptual basis for radar sounding based prospecting for ice. Left: radargram with hypothetical ice deposit and sources of noise. Right: Explanation of expected radar and neutron spectrometer data over five different amounts and forms of subsurface ice.*

Earth-based DSN stations. Lastly, imaging of the lunar subsurface with the existing Lunar Radar Sounder aboard the Kaguya spacecraft highlights the challenge of clutter from the Moon's topographic features that dominate subsurface radargrams in the 3-5 MHz range except for in the flattest of regions.

discussed here provides an order of magnitude higher resolution, however decimeter scale resolution is not achievable.

Potential Technological Solutions 2: Absolute radiometric calibration is possible capability with the addition of GPR at identified target sites in two

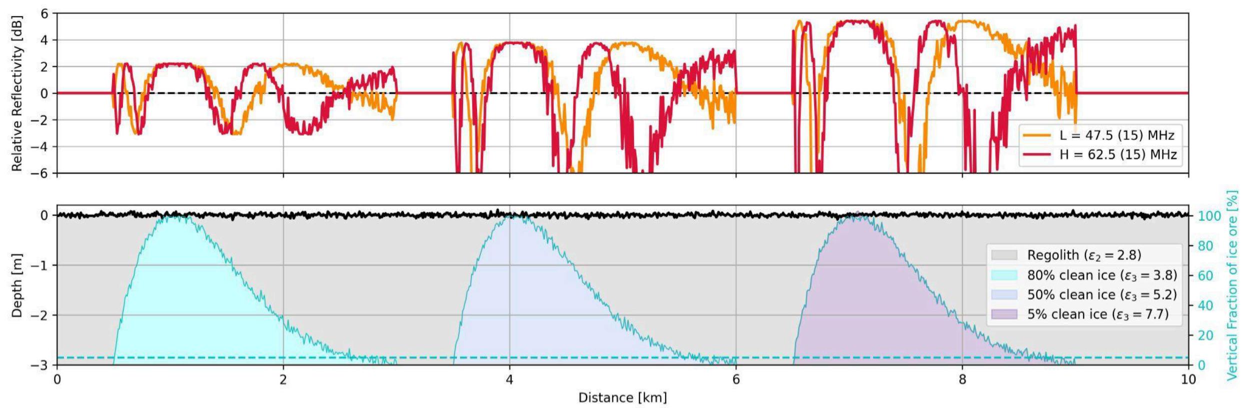

Figure 2. *Simulation of the expected radar reflectivity at 47.5 and 62.5 MHz center frequencies over shallow buried ice of different concentrations.*

Potential Technological Solutions 1: Our joint University of Texas at Austin and University of Arizona team is exploring solutions to these challenges. Specifically, a combination of optical navigation using crater topography and radar sounding of the Moon's surface can be paired to produce a terrain-based navigation system to accurately locate the SmallSat and its resultant datasets at a range of elevations. A high-resolution, fast gravity solution model can optimize guidance control solutions autonomously. We suggest with these guidance and navigation solutions, a SmallSat capable of determining ice content within the full regolith column is feasible. We propose combining a neutron spectrometer for ice detection in the top 1 m of regolith with a high-resolution radar that penetrates tens of meters into the subsurface and resolve physical interfaces in regolith and ice at 1.5-3 m vertical resolution and 0.4-1.2 km horizontal resolution for 10-100 km orbital altitudes (Figure 1). The radar also includes the ability to discern disseminated vs discrete bodies of ice via circular polarization ratio and radar reflectometry. Two radar solutions exist at the TRL 4-5 level requiring technical investment which should be paired with research into terrain-based navigation and autonomous guidance and control to realize this vision.

Technical Challenge 2: An orbital radar sounder is not radiometrically calibrated, limiting its ability to directly measure absolute dielectric properties. The only existing orbital radar data for the moon was the Lunar Radar Sounder collected at 3-5 MHz with wavelengths from 50-75 m. The proposed orbital radar

complementary ways: 1) geologic ground truth wherein a GPR can locally characterize the structure and properties of the ground to help calibrate the response of the orbital radar surface return, and 2) radiometric reference wherein one can design a radiometric link between the ground and orbital radars to provide a reference signal for absolute calibration. Moreover, GPR are necessarily higher frequency (due to antenna size among other issues) thereby providing a complimentary higher resolution dataset to pair with the orbital radar sounding data. Additionally, ground track spacing may be kilometers apart requiring significant improvement in horizontal resolution for subsurface data. Rover based GPR can be collected along closely spaced transects to assemble grids of data to bridge the prospect to resource scale level of mapping.

Parting Thoughts: Acquiring data in the third dimension (depths >1 m) and at a range of resolutions is critical for mapping on the Moon. Subsurface mapping through radar methods for science, lunar prospecting, and future resource production requires considering both orbital and ground-base solutions at nested resolutions with radiometric calibration.

References:

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