LOW-SWaP, HIGH RESOLUTION LIDAR: A CRITICAL ENABLING TECHNOLOGY FOR LUNAR SURFACE EXPLORATION. M. Zanetti[1], B. Robinson[2], P. Whelley[3,4], P. Bremner[1], K. Miller[1], [1]NASA Marshall Space Flight Center, Huntsville, AL, 35805; [2]Torch Technologies Inc, 4050 Chris Drive, Huntsville, AL 35812; [3]University of Maryland, College Park, [4]NASA Goddard Space Flight Center. (michael.r.zanetti@nasa.gov).

Introduction: Light Detection and Ranging (LiDAR) is a key enabling technology for terrain mapping, surveying, and autonomous scientific and civil engineering activities on the Moon. Here, we discuss the use of surface-based 3D scanning LiDAR technology to address specific challenges for the future exploration and operations of NASA's Artemis Program at the Lunar South Pole, as well as other regions to be visited by the NASA Commercial Lunar Payload Services (CLPS) and Payloads and Research Investigations on the Surface of the Moon (PRISM) programs. We describe the current challenges in lunar terrain mapping and navigation, discuss the benefits of LiDAR systems for addressing these challenges, provide operational concepts for tripod and mobile LiDAR scanning, and discuss potential drawbacks of LiDAR for planetary surface exploration. We conclude that active source LiDAR sensing is a critical technology to enable lunar exploration, particularly in the challenging environment of the Lunar South Pole.

Background: LiDAR determines angles and ranges from the sensor to objects by precisely measuring the two-way travel time of sent and returned light pulses. Within a field of view, 10^5 – 10^6 measurements per second are made. The exact mechanism of this measurement depends on the type of sensor used, but in general, a 3D representation of the surface can be created by capturing millions of range measurements as a point-cloud. Point clouds can then be used as a "digital twin" model of the scanned environment, allowing topographic, morphometric, and even built-environment characterization at the mm- to cm-scale, and over many hundreds of m^2. Furthermore, some LiDAR sensors, such as frequency modulated continuous wave (FMCW) LiDARs can also capture Doppler velocity for each range measurement, providing direct measurement of both motion in the scene and the sensor's movement within the scene. FMCW-LiDAR's capabilities can enhance navigation localization and scientific return [e.g. 1, 2]. Many different types of LiDAR sensors are currently used for terrestrial purposes (e.g. surveying, robotic and autonomous navigation of rovers and self-driving cars). For the case of lunar surface operations, we are primarily concerned with small, tripod- and mobile-platform sensors, which have never been used for surface operations. Such small, scanning LiDARs are a different class of sensor compared to orbiter assets, such as the Lunar Orbiter Laser Altimeter (LOLA), which have provided accurate maps of global topography, but at a much larger scale and different operating methodology.

Challenges in Lunar South Pole Terrain Mapping and Navigation: NASA's return to the Moon is providing new opportunities for in-situ analyses that have never before been possible. The major challenge for terrain mapping and navigation at the Lunar South Pole are:

Extreme low-angle solar illumination conditions and surface shadowing: At the Lunar South Pole (e.g., <85° S latitude) the sun does not rise above ~3° from the horizon, resulting in omnipresent long shadows from local topography and even small rocks and pebbles. Passive stereo-camera photogrammetry for accurate terrain mapping and navigation in these heavily shadowed terrains will be extremely challenging (if not impossible) and will not provide a dimensional measurement of the terrain with accuracy comparable to LiDAR. While remote tele-operated rovers (e.g. VIPER) will have the benefit of near-real-time human-in-the-loop navigational decision-making and flood-lighting to help discern terrain, future roving assets will require autonomous capabilities and active source vision-systems to be successful.

Lack of global positioning system (GPS: The issues associated with GPS-denied operation primarily affect mobile LiDAR navigation and mapping. The lack of shared, accurate reference timing and precise knowledge of position within a global reference frame can be overcome through advanced simultaneous localization and mapping (SLAM) algorithms aided by inertial navigation systems (INS) for use with LiDAR scanning.

Benefits of LiDAR for 3D surface characterization: LiDAR provides a hyper-accurate 3D representation of the topography of a scene, which can then be used for mission ops planning, local area context for science measurements at the landing site, geomorphometric measurements of the terrain (and even built-assets such as habitats), and execution of construction and other civil engineering tasks. Repeat scanning over time allows change detection and asset monitoring, which is particularly useful for sustained development of an outpost. Additionally, LiDAR allows for 3D virtual reconstruction of the scanned areas, facilitating mission operations planning and public engagement (i.e. "visiting" the landing site in virtual reality or augmented reality).

Characterizing Topography at the Scale of Surface Operations: Surface-based LiDAR scanning has the potential to close the resolution gap between existing orbital remote-sensing data and resolution needed for exploration and practical surface operations. Rapid, real-time, accurate physical measurement of objects, obstacles, and hazards greatly increases situational awareness and mission safety. The ultra-high-resolution (cm-scale) terrain maps can provide a quantitative measure of surface roughness, without altering the surface structure (e.g., fairy-castle structures) to inform analyses of photometry and radar reflectance. LiDAR data includes information about intensity and reflectivity, as well as polarization state (e.g., FMCW-LiDAR), that greatly enhances the scientific use potential beyond terrain mapping, to include supporting data for spectroscopy, thermal inertia, and other passive sensing methods. Additional velocity sensing capabilities, such as from FMCW-LiDAR, add uncharted potential for asset management (e.g., multiple rover "swarm" tracking, mobile construction monitoring, etc.).

Mapping in the Shadows (and Direct Sun): As an active-source vision and terrain mapping sensor, LiDAR can provide both navigational and scientific data while also operating in the shadowed terrains at the poles (e.g., areas of long-polar-shadows, permanently shadowed regions (PSRs), or even complete darkness); as well as combating solar opposition effects which "wash-out" visible topography. Additionally, some types of coherent LiDAR sensors (e.g., FMCW-LiDAR) are immune to solar interference, allowing direct up-Sun navigation. This capability can positively impact mission operations, allowing continued mapping without regard to the sun's position.

Challenges for adoption of surface LIDAR: LiDAR for planetary surface exploration such as described here presents engineering challenges. Chief among them are power requirements, data handling, and the paucity of high-TRL sensors (for extreme environments) that can be deployed for near term landed missions.

Size, Weight, and Power (SWaP): Operational requirements defined by concept-of-operations and mission operations place constraints on the types of sensors to be used. A sensor's range, accuracy, and precision specifications will need to be considered. Active-source sensors consume more power than passive sensors, and the longer the scanning range, the greater the power required. For comparison, most self-driving automotive industry-style sensors with 100-200m range may consume 10–30W. However, these power consumption levels are on the order of high-intensity lighting flood lighting for visibility, which would no longer be needed for hazard avoidance during roving.

Data Volume and Processing: LiDAR data processing to achieve ultra-high-resolution point clouds can be both computing resource and time intensive. Plus, data volumes from LiDAR scanners can be enormous, on the order of many tens-of-gigabytes depending on the balance of requirements for navigation, terrain mapping, and science. The benefits of number of points sampled per second have to be weighed against data volume. Correspondingly, how that data can be handled, compressed, stored, and transmitted/returned back to Earth requires attention and would need to be factored into engineering and mission ops requirements. A compromise between pure navigation (i.e. use-and-lose) and terrain mapping (i.e. scan-and-save) can be realized, but research into effective mapping strategies, path and/or scan-location optimization, and data compression techniques are needed.

***Leveraging Industry Research and Development*:** The self-driving automotive and autonomous robotics industries are major drivers of LiDAR sensor development and associated autonomous navigation research, as are areas of surveying, BIM/construction, and the construction of Digital Twins. Leveraging existing methodologies and technologies and adapting them for planetary science and lunar exploration will enable the rapid development that may be required for use in the Artemis program. Research in areas of AI and Machine Learning to optimize exploration, path-planning, and data handling will be key to maximizing the potential for LiDAR in planetary exploration.

Conclusions: LiDAR is a critical enabling technology both for planetary surface exploration and for sustained development of the lunar South Pole. Space-qualification of FMCW-LiDAR surface scanning LiDARs, suitable for robotic navigation and other mobile platforms (e.g., Astronauts), are currently under development, and existing high-TRL Mems-LiDARs can be miniaturized for surface operations [S, A]. On-board computing is already capable of handling LiDAR data processing but could be greatly improved with additional investment (e.g., space-qualified GPUs).

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