Applications of Mobile LiDAR for Ultra-High Resolution and GPS-Denied Terrain Mapping in Planetary Analog Environments. M. Zanetti[1], C.D. Neish[2], K. Miller[1], P. Bremner[1], E. Hayward[1], M. Adams[1], R. Perkins[2], S. Vanga[2], S.M. Hibbard[3], C.W. Hamilton[4]. [1]NASA Marshall (MSFC), Huntsville, AL USA, [2]University of Western Ontario, Canada, [3]JPL, Pasadena, CA, [4]University of Arizona, Tucson, AZ, USA. (Michael.R.Zanetti@nasa.gov).

Introduction: LiDAR scanning systems enable rapid and ultra-high resolution terrain mapping. In this study, we used person-mounted LiDAR systems to acquire data in the Holuhraun region as a planetary analog environment. The Holuhraun Lava Flow-Field was emplaced in Icelandic Highlands (–16.745 °W, 64.911 °N) in 2014–2015. Our study took place in conjunction with the 2022 Rover–Aerial Vehicle Exploration Network (RAVEN) field campaign in an area dominated by fresh spiny pāhoehoe and ‘a‘ā-like rubbly lava lobes that are partially mantled by aeolian sand ramps with numerous dune-like forms and ripples composed of sand and silt. The area represents a high-fidelity planetary analog environment, with lava and sedimentary landforms that exhibit morphologies, surface textures, and bedforms that are similar to both Martian and lunar surface environments. The site was also chosen for its accessibility, which facilitated comparisons of LiDAR systems with different capabilities, spatial resolutions, and relative accuracies with the goal of determining the accuracy of GPS-denied terrain mapping and navigation solutions – required for planetary surface exploration – relative to state-of-the art GPS-enabled systems. Data acquired along the same traverses enables us to evaluate the capability of mobile LiDAR technology for future planetary exploration.

Instruments: Two different backpack-mounted mobile LiDAR scanning systems were used. *The Kinematic Navigation and Cartography Knapsack* (KNaCK, [1]) is a development test article using velocity-sensing frequency modulated continuous wave (FMCW) LiDAR sensors to evaluate navigation and terrain mapping use in mobile (person- and rover-based) applications. The KNaCK consists of 2 different LiDAR sensors, an Aeva Aeries II FMCW-LiDAR [2] and an Ouster OS-1-64 (Rev 6, [3]) multi-beam flash LiDAR, both synchronized to a tactical grade Honeywell HG1700 inertial measurement unit (IMU) and GNSS via a Novatel PwrPak 7. The sensors are all collocated on the KNaCK with the Aeries II mounted forward-looking with a ~120° × 30° field of view (FoV) and ~200 m range, and the OS-1 mounted on the rear of the platform with a side/downward looking orientation, a 360° × 45° FoV and ~100 m range. The range resolution of each of the KNaCK-mounted scanners is similar, with ~3–5 cm accuracy at ~50 m (and low reflectance of the Icelandic lava terrain in this test). Both sensors are capable of >1 million points/second; however, due to data volume from a slow-moving user and computational factors, point clouds were down sampled to 10 cm spacing. Both the Aeries II and OS-1 sensors broadcast multiple beams allowing for the use of simultaneous localization and mapping (SLAM) algorithms which enable terrain mapping in GPS-denied environments. To test the accuracy of a custom SLAM algorithm (KNaCK-SLAM, [4]) Aeries II and OS-1 data were processed both with and without global positioning data, providing an accuracy comparison of GPS-denied mapping to GPS-enabled ground-truth.

The *Phoenix LiDAR [5] – Ranger LR system* consists of a Riegl VUX-1HA sensor mounted with side/downward FoV with a tactical grade IMU-52 (LN200C) IMU. The VUX-1HA is a premium 360° single-line sensor with sub-cm range precision and >>300 m maximum range and capable of >1.5 million points/second and 250 lines/second. A comparison of the processed data quality between the Phoenix Ranger and the KNaCK OS-1 sensor is shown in Fig. 1, with digital elevation models after post-processing of 3cm/pixel vs 10 cm/pixel. The range precision is effectively an order of magnitude better for the VUX-1HA compared to the OS-1-64 (Rev 6). The primary drawback to a single-line scanner, however, is that it cannot be used for SLAM processing, and thus cannot

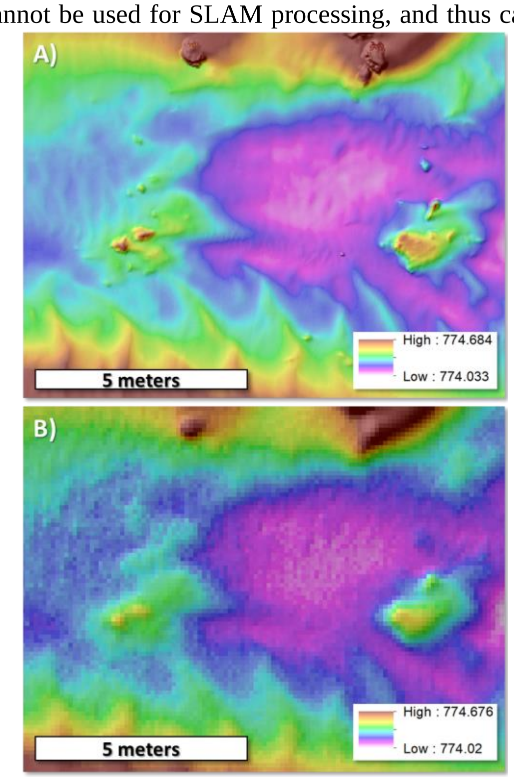

Figure 1: LiDAR imaging of the Holuhraun lava margin. A) Ranger LR VUX-1HA DEM 3 cm/px resolution versus B) KNaCK Ouster OS-1-64 (Rev6) 10 cm/px resolution.

be used for terrain mapping in areas without GPS positioning.

Methods and Results: Data from the KNaCK and Ranger systems were collected contemporaneously following an identical ~400 m traverse and GPS signal conditions. Differences in data collection are therefore primarily related to sensor FoV and attributes of the technology used, rather than due to specific operator influence (although operator experience and traverse path can impact end-product quality). Data were pre-processed using scanner-specific software, which all involve the fusing of GPS position, IMU orientation, and LiDAR point-cloud data. Data were georeferenced to UTM28N-NavD88. All point clouds were imported, cleaned to remove isolated points and noise outliers >20 cm, and aligned using CloudCompare [6]. Due to the extremely high density of Ranger LR data, point clouds were subsampled to 1 cm spacing to ease computational load. Point cloud alignment were completed using OS-1 as a reference on 1M pts with final unweighted RMS of 5cm for Ranger LR, 6.2 cm for Aeries II, 6.7 cm for OS-1-noGPS-_LoopClosed, and 7.8cm for OS-1-noGPS_noLoop. (Loop closure is a method in SLAM processing that improves the solution when the sensor can recognize that it has returned to a previously known position). Maps for OS-1 and Aeries II (with and without GPS) and Ranger LR (with GPS) were exported as georeferenced rasters into ArcGIS 10.8 where difference maps were calculated (with no additional georeferencing). Figures 2A–C show a sample of the DEMs created with their respective areal coverage (related to scanner FoV, where no-data voids indicate LiDAR shadow). Figure 2D-F show the elevation difference from the OS-1 reference.

Discussion: The Ranger LR scanner provides exceptional spatial resolution (3 cm/pixel or better, Fig. 1a), allowing for high-resolution morphologic measurement and terrain characterization but requires GPS and areal coverage can suffer due to LiDAR shadow (mitigated by longer or more complicated traverses). Aeries II FMCW-LiDAR offers very good range and coverage (i.e., fewer shadows vs Ranger LR), with the added benefit of multiple scan lines and Doppler velocity measurement—an inherent 6° of freedom (6-dof) “ego”-state estimate informing orientation and position—improving GPS-denied mapping accuracy. OS-1 represents a compromise with excellent areal coverage at ~10 cm/pixel resolution (soon to be improved with new Rev-7 sub-cm-precision sensors), and with multiple scan lines allowing for GPS-denied SLAM processing. Figure 2D (GPS-enabled and GPS-denied-loop closure) shows how the accuracy of the data changes due spatial differences in the processed map. In the GPS-denied mapping case, while the map appears to contain no obvious position errors, when compared with a GPS-enabled ground-truth from the same sensor some features are out of position by up to ~1 m. (While an outstanding result as it does not rely on GPS, morphologic measurements would be inaccurate and this error would need to be accounted for).

Acknowledgments: MSFC personnel were supported by the NASA STMD ECI and SMD ISFM programs. We thank the NASA PSTAR RAVEN project (PI: C.W. Hamilton) for their collaboration. C.D. Neish thanks the CSA FAST program. We also thank Aeva, Inc. and Ouster Inc.

References: [1]Zanetti, M. et al, (2022),LPSC53#2634. [2] Aeva.ai.[3]Ouster.io.[4]Miller,K. et al, (2022) LPSC53, 2808. [5]phoenixlidar.com. [6]CloudCompare.org, V2.12.4, GPL

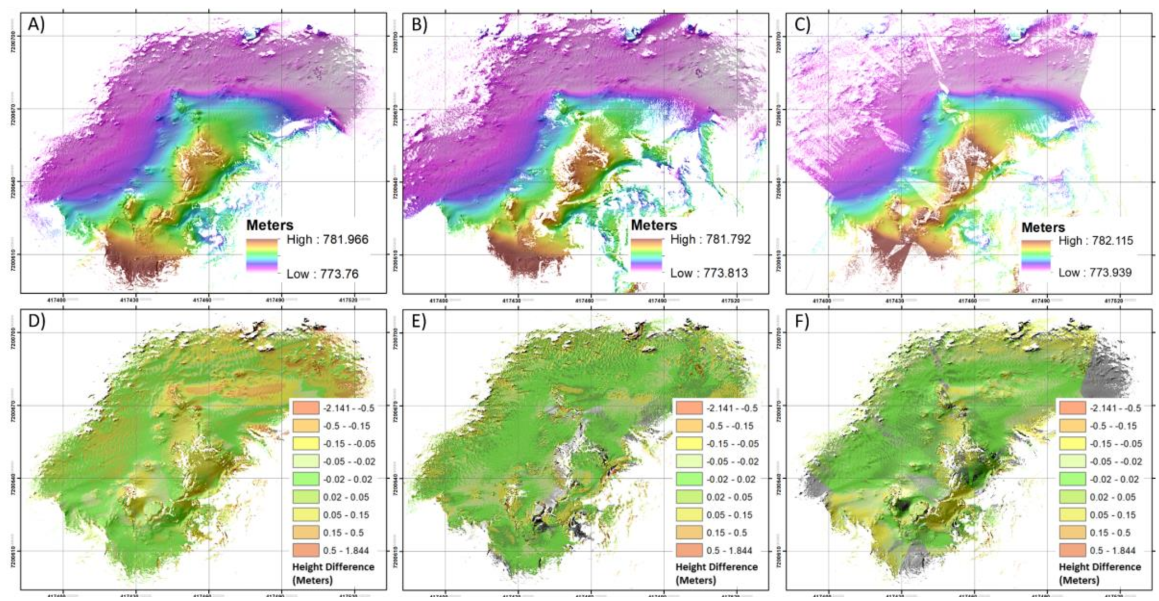

*Figure 2: **DEMs** A) KNaCK Ouster OS-1 10 cm/px; B) KNaCK Aeva Aeries II 10cm/px map, C) Ranger LR Riegl VUX-1HA 3 cm/px. **Difference maps (vs OS-1-GPS)**: D) OS-1 GPS-denied (note large variations due to spatial accuracy variation), E) Aeries II, F) VUX-1HA. Note extensive areas within ±2 cm in all difference maps, indicating high correlation in aeolian areas.*