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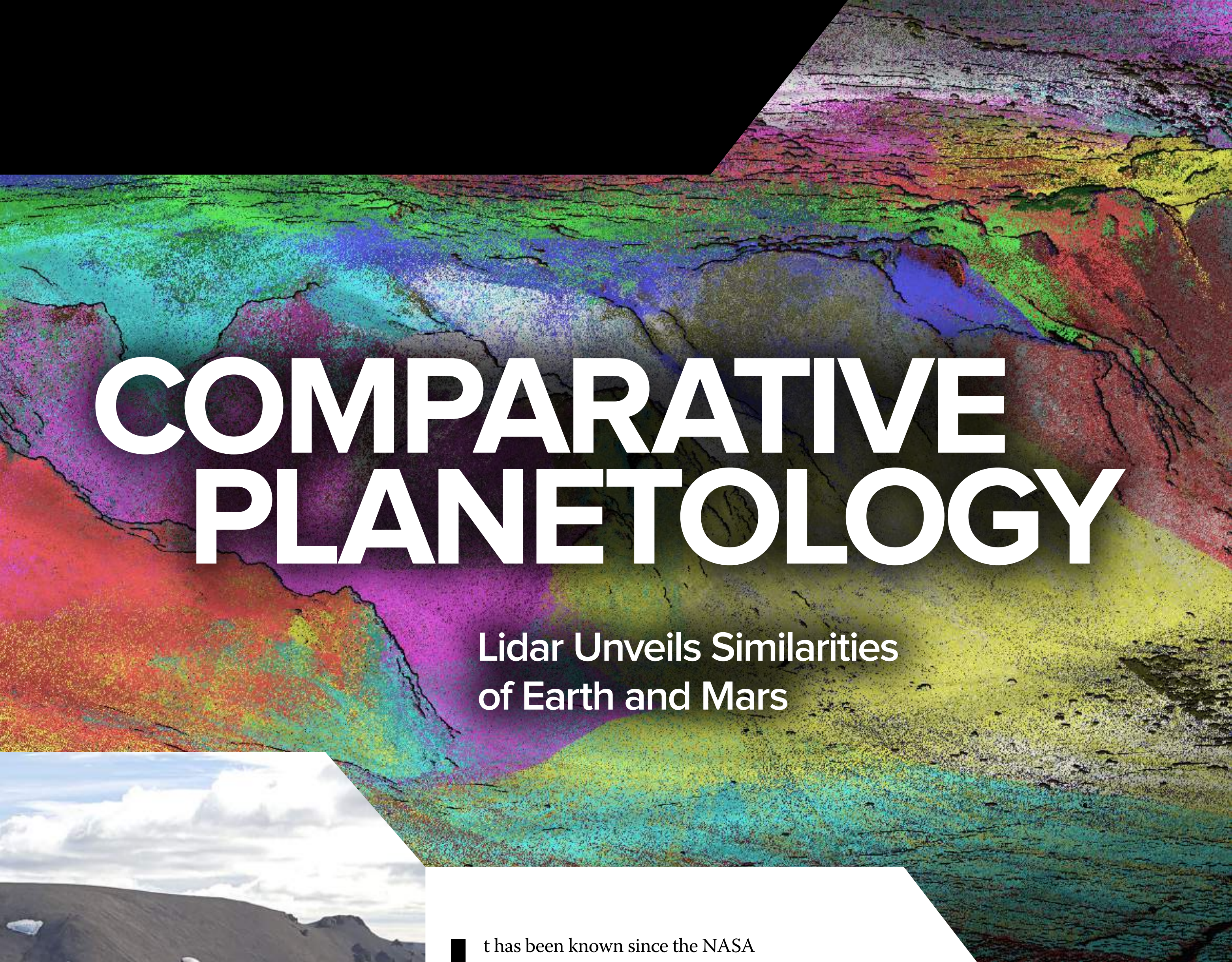
COMPARATIVE PLANETOLOGY



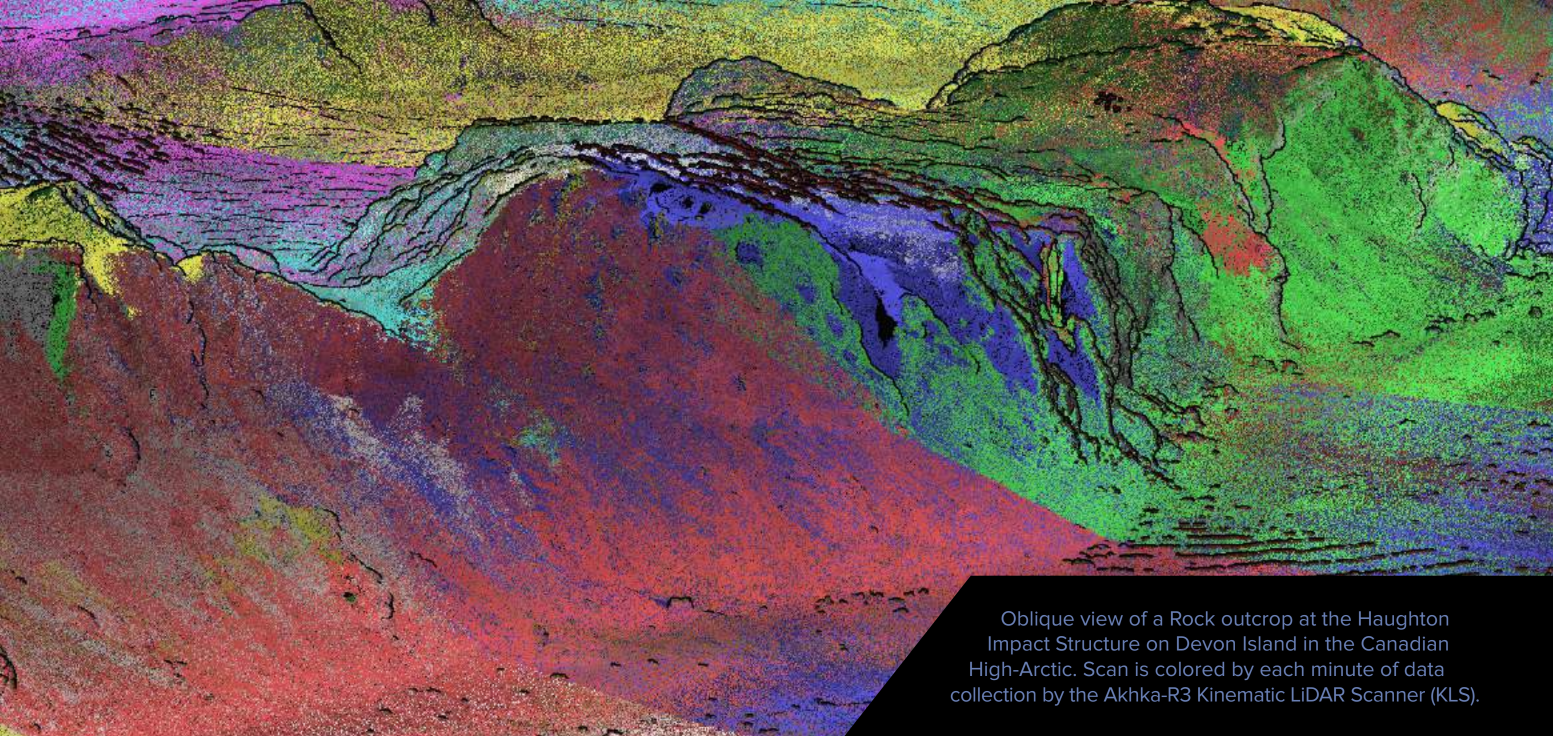
COMPARATIVE PLANETOLOGY

Lidar Unveils Similarities of Earth and Mars

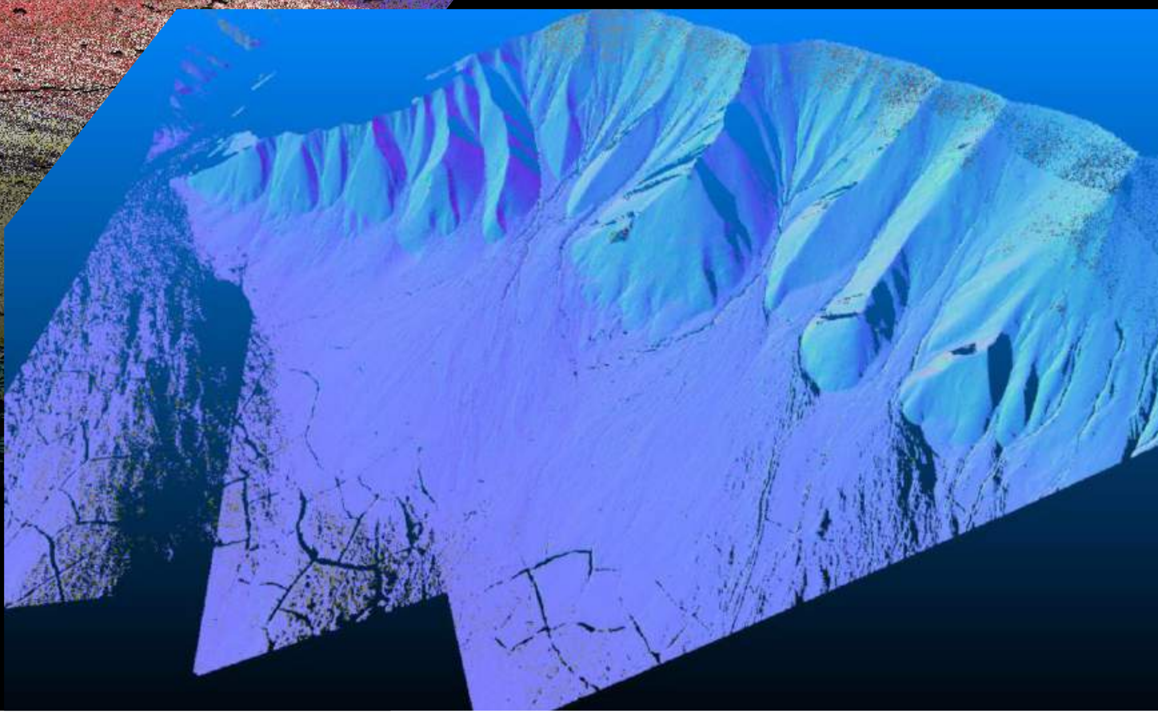
Team member (M. Zanetti) traversing with the Akhka-R3 Kinematic Lidar System (KLS) in the Haughton Impact Structure on Devon Island in the Canadian High-Arctic.

It has been known since the NASA Viking orbiters and landers of the 1970s that the surface of Mars is similar to Earth in many ways. Mars has evidence of rivers, outwash channels, and glacial features indicating an important role for water throughout its geologic history. However, Mars is not Earth. Despite geomorphologic similarity, the underlying processes that shaped Mars' landscape may be quite different between the planets. Our group specializes in Comparative Planetology, which as the name suggests, compares geologic features between the terrestrial planets (Mars, Venus, Mercury, and the Moon) to understand the fundamental processes driving their shapes and patterns. We mostly use remote-sensing datasets from satellite orbiters and robotic landers that include high-resolution imagery, topography from laser altimetry and stereo-photogrammetry, radar backscatter, and spectrometry. However, there is an essential need for ground-truthing of these datasets to understand their limitations and what they are actually telling us. Since Mars is a difficult place to visit, we study analogous features on Earth using comparable datasets. The benefit is two-fold: we can investigate the

BY MICHAEL **ZANETTI**, ANTERO **KUKKO**, CATHERINE **NEISH**, & GORDON **OSINSKI**



Oblique view of a Rock outcrop at the Haughton Impact Structure on Devon Island in the Canadian High-Arctic. Scan is colored by each minute of data collection by the Akhka-R3 Kinematic LiDAR Scanner (KLS).



Right: Gullies cutting into hillslope in the Haughton River Valley scanned with the Teledyne Optech Polaris. Total vertical relief ~250 m.

geologic and geomorphologic processes shaping the earth in detail, helping to better understand our own planet and our own remotely-sensed data, and we can apply these Earth-based observations and measurements to infer the processes acting on the other terrestrial planets, accounting for different planetary conditions (*e.g.,* gravity and climate).

The Canadian High-Arctic shares a geomorphologic similarity with the middle and high latitudes of Mars, as both have many cold-climate landforms related to the presence of ground-ice (*e.g.,* glacier-like flows, polygonal patterned ground, debris-flow gullies). Now, using ground-based lidar scanning, and in particular ultra-high resolution mobile lidar scanning techniques, it is possible to study these systems in unprecedented detail and over areas that would have been unimaginable a decade ago.

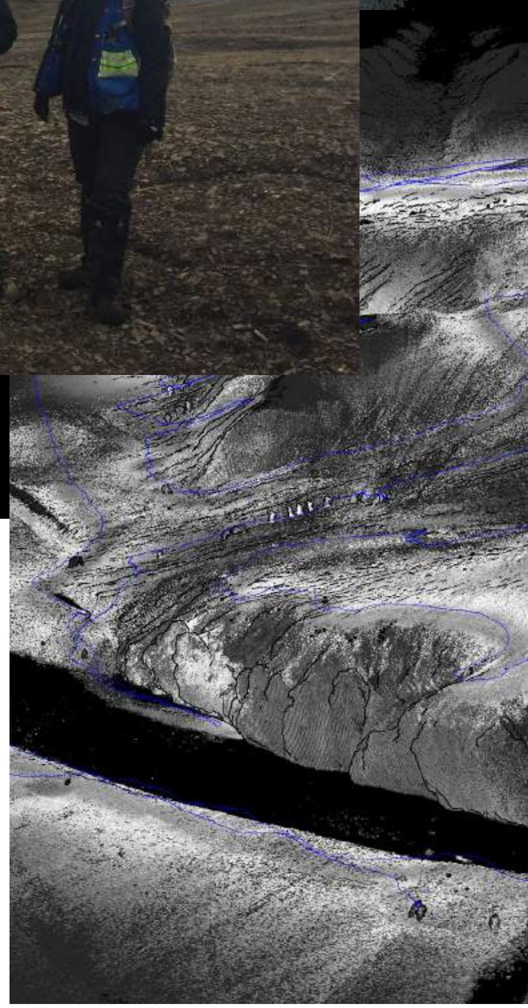
As part of planetary analog expeditions in 2016 and 2017, researchers from the University of Western Ontario and the Finnish Geospatial Research Institute, together with industry support from Teledyne Optech, set up camps on Devon Island 75°22'26.52"N, 89°31'47.70"W and Axel Heiberg Island 79°16'11.61"N, 90°19'46.25"W to map and measure gullies and patterned ground using a suite of the latest generation tripod and mobile lidar scanning systems. Our lidar mapping has returned measurements of surface topography at

Network of erosional gullies covering ~2 acres (~2.5 billion points) in the Haughton Impact Structure mapped by hiking channels and ridge lines. Scanned with the Akhka-R3 KLS and color coded by each minute of data collection.

Axel Heiberg team members (G. Osinski, M. Zanetti, E. Harrington). A custom backpack rig was made for the Teledyne Optech Maverick mobile scanner.

unprecedented resolution (<2 cm/pixel DEM raster resolution) and is allowing us to break new ground by using mobile lidar for geomorphology research. The speed and repeatability of lidar scanning means: 1) more area is covered, which allows for study of the interplay between different morphologic features and processes, 2) less time is required, which allows researchers to do different experiments or measurements, and 3) inter-season or year-on-year change detection is possible, which allows for the determination of rates-of-change and the effects of small perturbations not captured in long-duration investigations.

The aim of the expeditions was two-fold. First, we want to advance our fundamental understanding of permafrost processes over large areas. As the Arctic climate warms, our understanding of changes within permafrost systems needs to be more complete, and the rapid data-acquisition and ever-higher point density and precision from mobile lidar systems can help monitor these changes over time. This has implications for understanding how to build better buildings and roads in the Canadian North as climate warms and ground ice melts. Understanding how these systems change over time will also address challenges with building permanent structures in permafrost terrain.

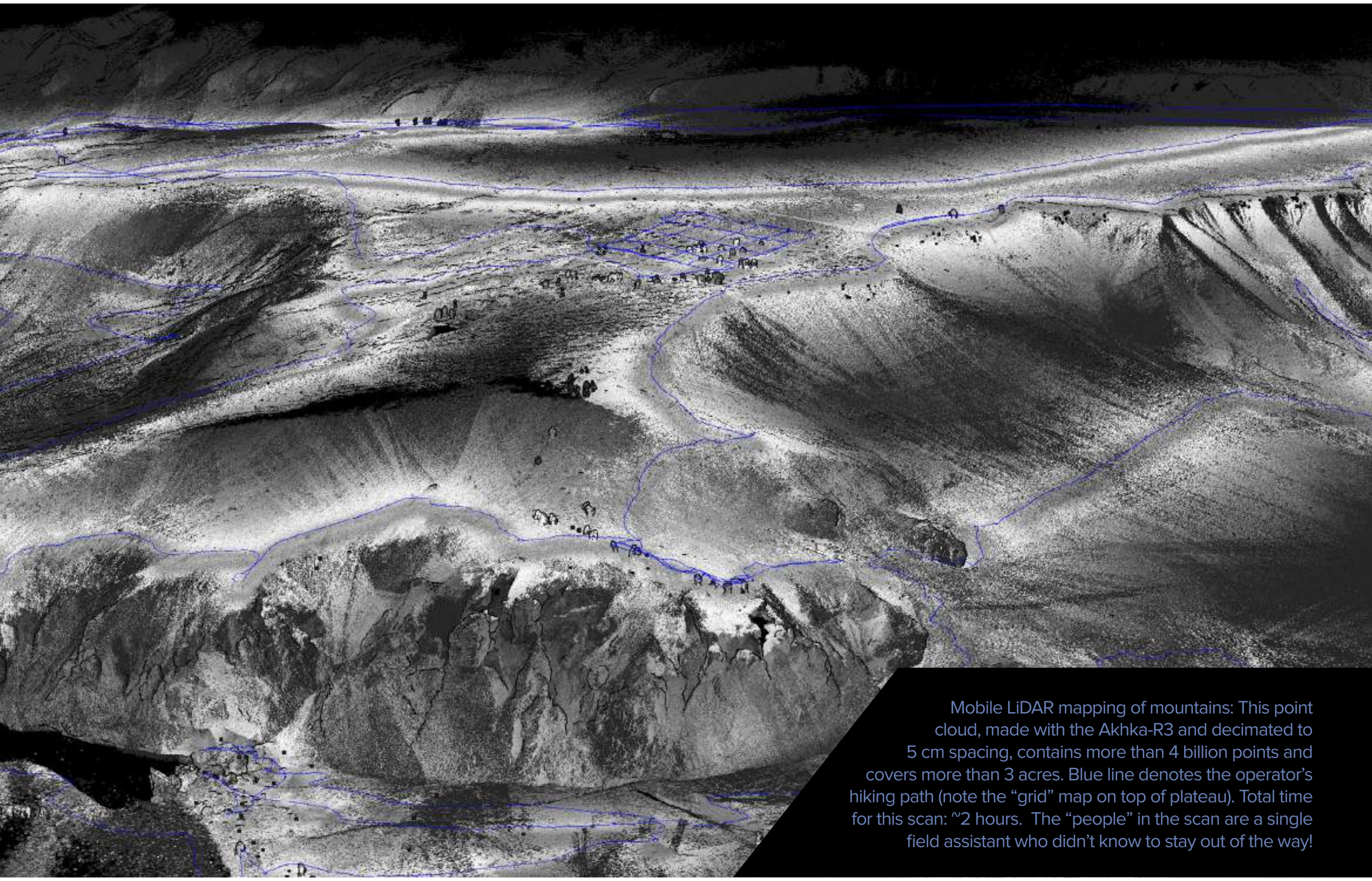


Second, we want to understand permafrost systems from a planetary perspective and examine how differences in planetary gravity, atmospheric density and composition, and even the rotational axis of Mars affect the formation of these features on Mars. Ground ice is likely to be an important resource for future manned missions to Mars, since water-ice can be used for both drinking and rocket-fuel, and comparative planetary geomorphology allows us to identify where and how accessible this water might be.

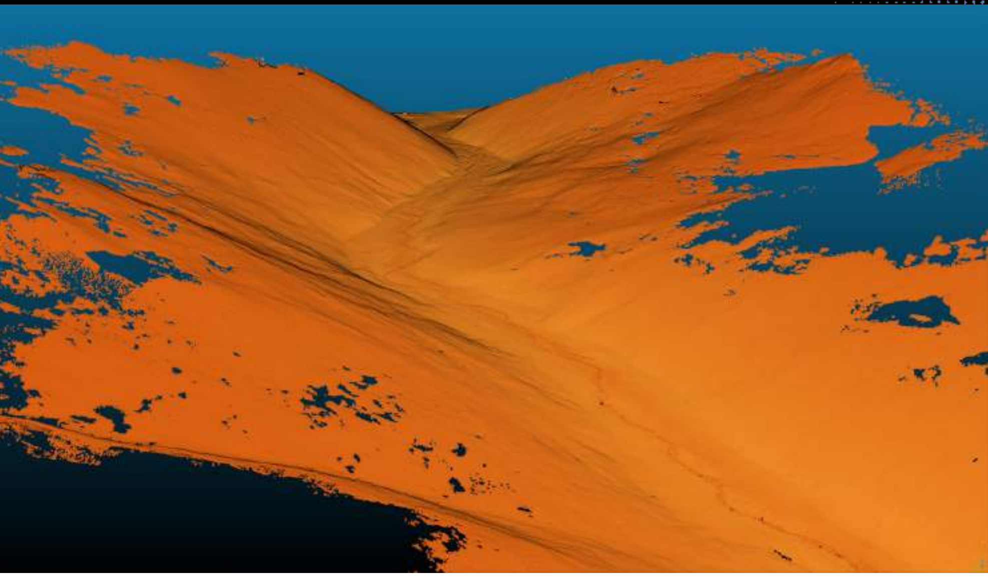
Cold-Climate Landforms on Earth and Mars: Freeze-Thaw on Earth

The daily and seasonal freezing and thawing of the ground in the Canadian High Arctic wreaks havoc on the bare rocks and soil. The volume expansion of water when it freezes in pores and cracks forces rocks to break apart and the ground to fracture. These effects are fairly commonplace in the winter in colder climates, causing potholes in roads and roof damage from backed-up gutters. But in the High Arctic, there are no trees and little vegetation to hold rocks and soil in place, thus freezing, thawing, cracking, and heaving causes much movement of the surface.

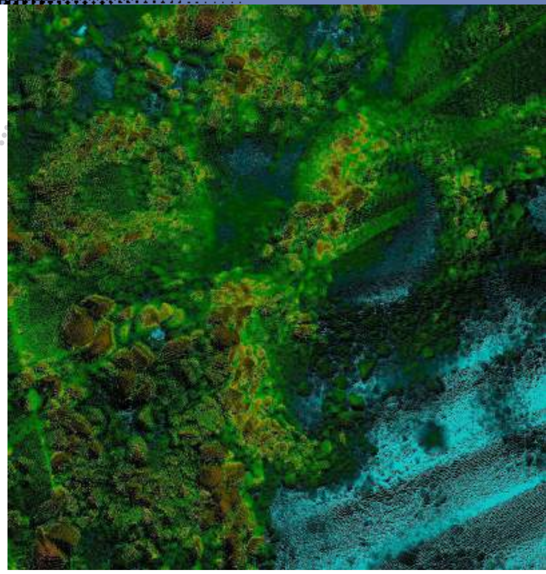
The ground of the High Arctic is permanently frozen (permafrost) below a few tens of centimeters of the surface. But within the upper zone, known as the active layer, seasonal freeze-thaw processes work in pore-spaces to sort stones and soil into patterns (imaginatively known as "patterned ground" in geomorphology parlance). When water infiltrates



Mobile LiDAR mapping of mountains: This point cloud, made with the Akhka-R3 and decimated to 5 cm spacing, contains more than 4 billion points and covers more than 3 acres. Blue line denotes the operator's hiking path (note the "grid" map on top of plateau). Total time for this scan: ~2 hours. The "people" in the scan are a single field assistant who didn't know to stay out of the way!



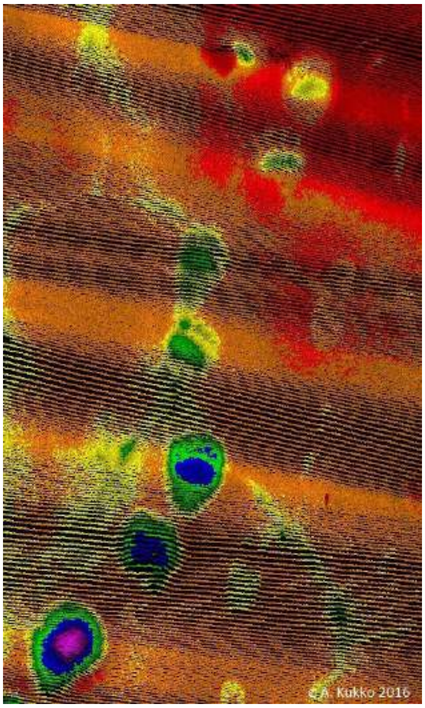
Oblique view of a "tunnel" valley, a channel originally formed beneath a glacier. The cloud is the result of a single pass walking down the centerline of the channel.



KLS scan of stone circles on Devon Island, approximately 1 m in diameter and 20-30 cm high. Stone circles, formed by frost heave and sorting, are a common type of patterned ground seen in permafrost terrains on Earth and Mars.

longer cracks, freeze-thaw processes work to propagate these cracks into fissures (ice-wedges), which then become intertwined and form polygons, creating checkerboard patterns that can cover many square kilometers. On hillslopes, thawing of snowmelt and permafrost at the margins create debris-flows and rockslides, etching into and eroding the landscapes.

These phenomena and the processes controlling them (technically known as periglacial features and processes) have been known and described since the early 1900s, with pioneering work detailing patterned ground done from the 1950s through the 1970s. At that time the characterization of these phenomena (measuring diameter, spacing, trough-depth, and other morphometric parameters) was done with painstaking and unsophisticated manual measurements. For example, year-on-year and decadal changes were measured using marked sticks shoved into the ground. The time-intensive nature of the measurements meant that only small areas could be investigated, mostly in isolation from nearby features.

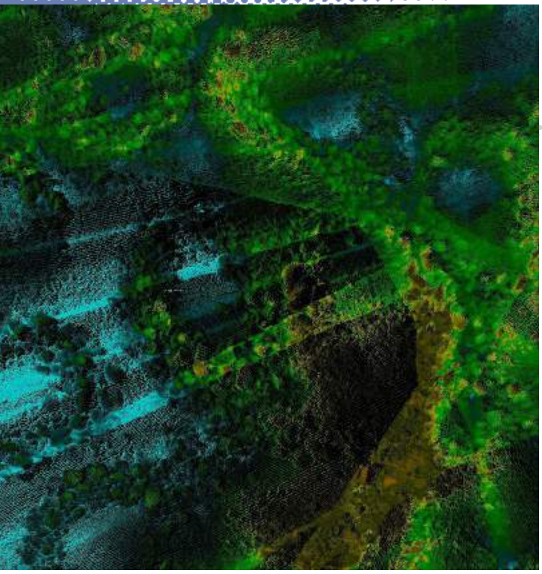


Polar bear footprints preserved in fresh mud near our Devon Island campsite. Although bear encounters are rare, all expedition members have firearms training and carry rifles on sorties. Note the operators footprints to the right of the bear tracks.

Processes Shaping the Surface of Mars

Mars is cold, but not as cold as one might expect. Although the yearly average temperature is around –55 °C (–67 °F), air and ground temperatures as high as 35° (95°F) have been measured by landed spacecraft. With these temperatures, one might expect that liquid water on the surface would be common, but it is not. The reason for this is that Mars has a very thin atmosphere, with very low atmospheric pressure (~6 mbar, ~1% of Earth's). What is exceptional about the Mars climate is that it can be close to the "triple-point" temperature/pressure of water (6.1 mbar, ~0°C), where all three phases (solid ice, liquid water, and gas vapor) can exist at the same time. For the most part, water only exists in either solid (ice) or gaseous (vapor) phases, and changes directly between these states (sublimation from a solid to liquid, deposition from a gas to a solid). Liquid water only exists in a transient state before it either freezes or boils.

The impermanence of a liquid phase of water on Mars has consequences for interpreting its surface geomorphology. Freeze-thaw processes like those in the Canadian High-Arctic might be possible during brief excursions in the planet's obliquity (see sidebar on page 32), but we don't really know if the transient water available is enough to explain the



widespread polygonal ice-wedging we see on Mars. Scientists alternatively consider the idea that sublimation and deposition of ice (with no water phase) can produce the same patterns and shapes, albeit over much longer timescales than would be possible with freeze-thaw processes. Similar to 'ice-wedging,' thermal contraction of the ground creates a crack and exposes near-surface ice, allowing for sublimation to create void spaces in the ground. These pore spaces collapse or are filled with dust and sand producing 'sublimation polygons' or 'sand-wedges.' Such phenomena are found on Earth in the Antarctic Dry-Valleys, but are rare. A sublimation-driven explanation for the morphology is mechanically very different from a freezing-water expansion mechanism. Deposition of ice from a vapor does not produce the same amount of 'wedging' force that freezing does, which would affect the morphologic characteristics of the Martian features.

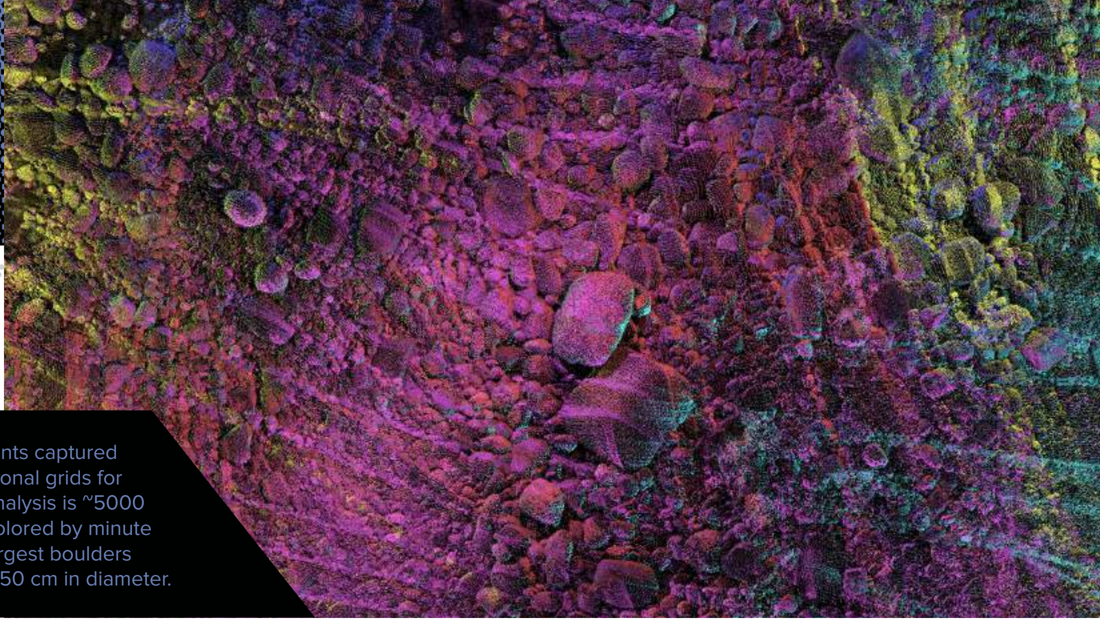
Expedition team member C. Neish captured in a KLS scan while recording handheld GPS points. KLS scans with the Riegl VUX-1HA were taken with 1 million points/second and 120 line/second, resolution high enough to even capture dangling backpack straps.

Since we know that 'ice-wedging' is the driving process in the High-Arctic, and if the morphology of Mars features are similar, our measurements may show that freezing water is necessary to explain their formation. If this is the case, then it is another important piece to understanding the very-recent geologic history of Mars.

Science Expeditions to the Canadian High-Arctic

Over the course of three expeditions in the extreme Canadian High Arctic environment on Devon Island and Axel Heiberg Island, we field tested three different lidar systems and evaluated their use for different geomorphologic measurements. Optech provided two of their newest generation scanners, a Polaris Terrestrial LiDAR scanner (TLS) and a Maverick Mobile Mapping System. Our collaborator A. Kukko at the Finnish Geospatial Research Institute provided their Akhka-R3 Kinematic LiDAR System (KLS). Each instrument produced high-quality data, yielding more than 400 Gb of mobile and TLS lidar data, but highlighted the importance of choosing the right tool for the job. To our knowledge, our expeditions are the first to use mobile lidar scanning systems to address geomorphology related questions and to be deployed in the Arctic.

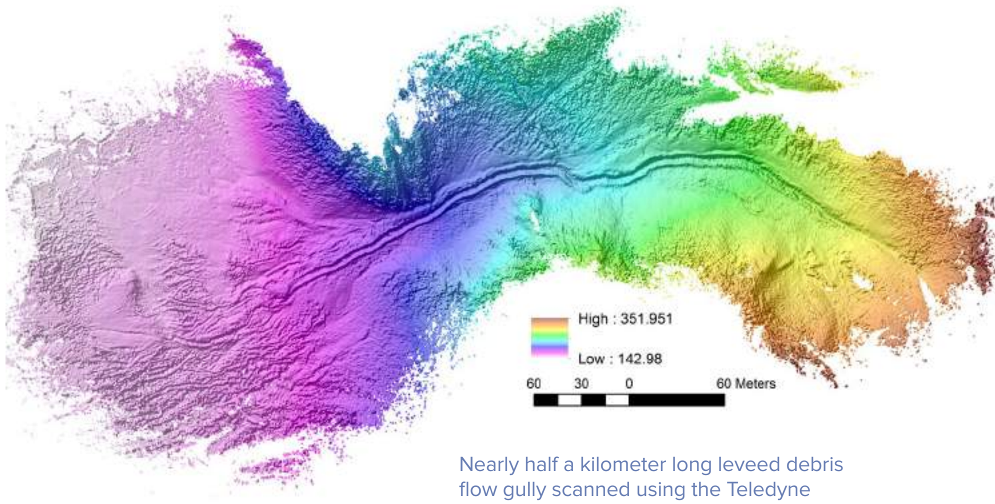
Although a major focus of the expeditions is our comparative planetology research, the lidar data we collected is being used by our team for a wide range of science investigations. Our main field projects involved surveying and mapping patterned ground, ice-wedge polygons, debris flows and channeled slopes, and sub-glacial drainage channels in order to measure various morphometric parameters—length, width, diameter, depth,



Typical density of points captured when walking orthogonal grids for surface roughness analysis is ~5000 point/m². KLS scan colored by minute of data collection. Largest boulders near the center are ~50 cm in diameter.

etc. These data are used in concert with ground probe data, geologic mapping, and remote-sensing datasets to interpret the underlying geologic processes acting to shape the landscape on Earth. Looking forward to future expeditions planned in 2018 and 2019 (and with other lidar data collected over the past decade), we will measure small-scale year-on-year changes to establish rates of change for these systems. To apply these data to Mars we are using the stunning 25 cm/pixel imagery and ~2 m/pixel DEMs from the High-Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO) which clearly show the morphology and extent of patterned ground and hillslope channels.

The individual scanning sites are also part of an overarching project aimed at using remote predictive mapping techniques to explore the geology of the Canadian High Arctic. The prohibitive cost and logistical challenges of geologic mapping with field geologists in remote areas means that many areas have never been studied. We are using integrated remote-sensing datasets such as LANDSAT-8, ASTER, RADARSAT-2, Quickbird, etc., to identify sites of interest for ground-truth field campaigns. The characteristics of these sites in terms of composition, roughness, and topography allow for educated interpolation of geology over large regions, with particular interest in economically viable ores. The high-resolution lidar topography helps us understand and interpret the satellite radar backscattering signals because we can now accurately measure the surface roughness at length scales below the radar wavelength, and over areas on the ground large enough to cover multiple radar image pixels.



Nearly half a kilometer long leveed debris flow gully scanned using the Teledyne Optech Maverick instrument on Axel Heiberg Island. Debris flows such as this are common in middle latitudes of Mars, and our lidar measurements can help determine the evolution of these systems.

Our Field Sites

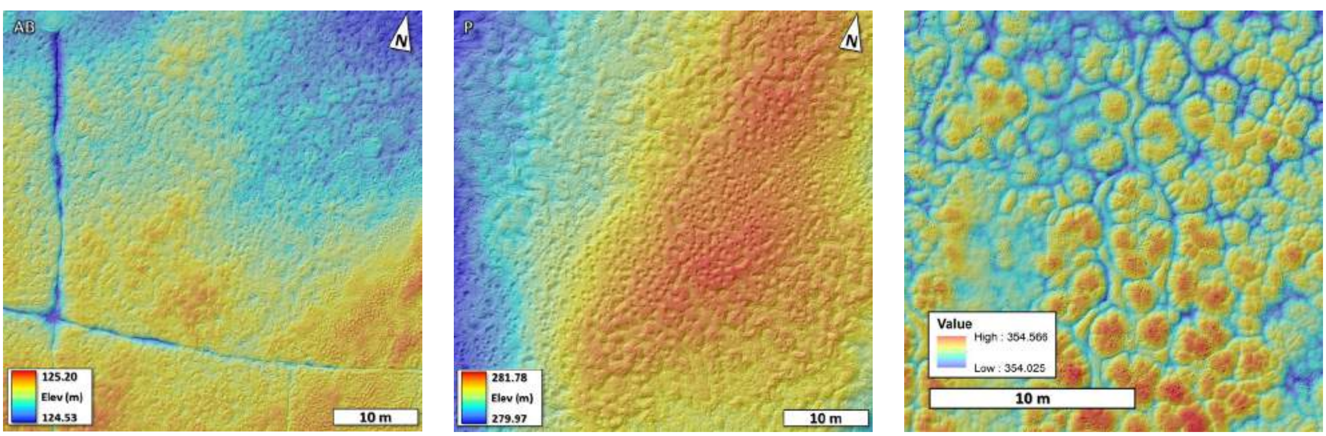
We mapped more than 50 sites of interest on Devon Island and Axel Heiberg Island. On Devon Island, the largest uninhabited island in the world, our primary field site was located within the Haughton Impact Structure, a well-preserved 39 million year old, ~23 km diameter impact crater. This site is regarded as one of the best Martian analogue sites on Earth, since it has similar rock types, a polar desert climate, and is within an impact crater (the most ubiquitous geologic structure in the Solar System). On Axel Heiberg Island we were based out of Strand Fiord, a glacier carved valley known for salt tectonics and mineral springs. The two islands offer stark contrast to one another, with Axel Heiberg dominated by mountain peaks and temperate glaciers and Devon Island dominated by desolate, bare plateaus.

To get to our respective basecamps on the islands we flew in with all of our gear on Twin Otter aircraft from Resolute Bay, a community of approximately 200 people and home to the Polar

Teledyne Optech Maverick system carelessly left on the ground near our campsite on Axel Heiberg Island. Maverick scans of patterned ground and debris flow gullies were done using a custom built backpack mounting frame.

Continental Shelf Program logistics facility. We used several Kawasaki Bayou 200 ATVs on Devon and two mountain bikes equipped with fat tires on Axel Heiberg for traveling to local sites, and we also logged about six total days of helicopter time to shuttle us to more distant sites. We bunked in individual tents and shared a common "Space-dome" tent and a separate cooking tent. On these large scientific expeditions we had some amenities, including a proper touch-screen desktop computer for planning, uploading data each night, and discussion, plus a movie when the weather turned awful. The weather at this high latitude is variable, but surprisingly not as frigid as one might perceive "polar" research to be. Temperatures hovered around 1-5°C (32-41°F), with some days above 10°C (50°F). Drizzle and cloud cover were frequent, slowing data collection, but fresh snowfall was rare. The greatest benefit to Arctic research in the summer is the 24-hour sunlight, allowing for scanning at all times. If poor weather affected some part of the day we could always pick up the time later. My partner and I would often head out for several hours of scanning at midnight, since this seemed to be the time of day when the sun liked to shine.

Because we were in such remote and rugged terrain, the instruments were subjected to the cold nearly constantly. Cold-sinking the instruments overnight meant that we needed to bring them into the communal tent after breakfast to "get some heat in them". We would hook them up to direct power while we loaded our ATVs and got water for the day. This typically let us hit the ground running when we got to our first site, but on more than one occasion we lost data collection opportunities. Battery life was also an issue, requiring multiple spares and nightly charging with a portable generator.

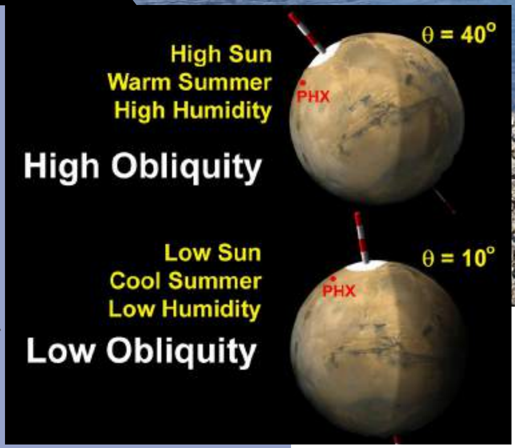


Examples of 50 m x 50 m grids used to compare surface roughness and satellite radar backscatter. The ultra-high resolution (<2 cm/pixel) DEM rasters show the variability of patterned ground and its dependence on rock types. (KLS data, note the vertical scale bars).

MARTIAN REALITY

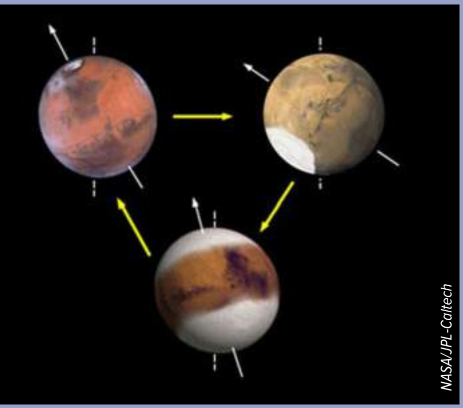
Like a toy spinning-top, the rotational axis of a planet can be wobbly. The change of the tilt-axis angle (obliquity) and tilt-direction towards the sun (precession), known as Milankovitch cycles, play an important role in how the climate of a planet changes over time. The amount of solar radiation (sunlight) different parts of a planet receives is related to these wobbles. As a planet tilts more towards the sun, high latitudes and the poles receive more sunlight (and low latitudes and the equator less). Earth has a large moon that helps stabilize these wobbles to between 22.1° and 24.5° from vertical over some 40,000 years), but even this small 2° difference can account for ice-ages.

The obliquity of Mars can change by a whopping 47° over 100,000 years or so, creating massive changes to the planet's climate. When these large excursions occur, the poles of the planet receive much more sunlight, causing the ice caps to sublimate, increasing the atmospheric density. Water and carbon dioxide vapor in the atmosphere is then transported equator-ward. The water vapor is then deposited or condensed as snow, which is then mixed with dust and sand, creating thick dust-ice mantles that blanket the middle latitudes. As the obliquity of Mars returns to a more vertical orientation, the ice deposited in those middle latitude areas is then sublimated again back to the poles, leaving behind the dust and sand, creating enigmatic erosional shapes and patterns. The changes in the atmospheric pressure, local temperatures, and availability of water together make freeze-thaw processes more likely to occur, shaping the Martian landscape by processes similar to those in the Canadian High-Arctic. It is likely that many 'fresh' appearing features, such as patterned ground, ground-ice polygons, and debris-flow gullies have been formed during recent obliquity excursions. Our lidar measurements from Devon Island and Axel Heiberg are helping constrain the conditions necessary for widespread patterned ground and how it can be applied to Mars.



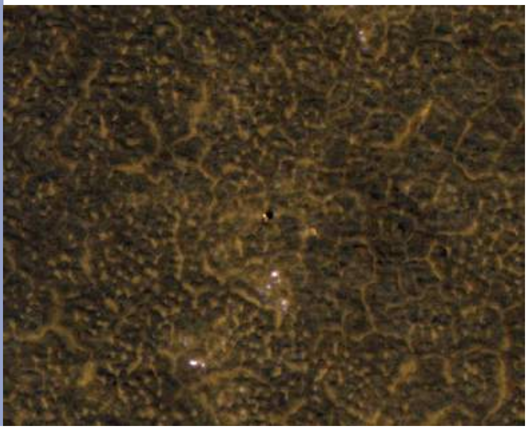
NASA/JPL/University of Arizona

Variations in Mars Obliquity and conditions at the Phoenix Mars Lander site (marked in red PHX).
nasa.gov/mission_pages/phoenix/images/ReplaceObliquity_002.html



NASA/JPL-Caltech

Modern-day Mars experiences cyclical changes in climate and, consequently, ice distribution. Unlike Earth, the obliquity (or tilt) of Mars changes substantially on timescales of hundreds of thousands to millions of years. At present day obliquity of about 25-degree tilt on Mars' rotational axis, ice is present in relatively modest quantities at the north and south poles (top left). This schematic shows that ice builds up near the equator at high obliquities (top right) and the poles grow larger at very low obliquities (bottom)
(References: Laskar et al., 2002; Head et al., 2003).
https://www.nasa.gov/mission_pages/msl/multimedia/pia15095.html#.WqWZVXxG1hE



Patterned ground at the NASA Phoenix Mars Landing Site. Lander (at center) imaged by the HiRISE instrument camera with 25 cm/pixel. Image is ~138 m wide. Note the similarity of patterned ground here to our lidar measurements.
Image credit (NASA/JPL-Caltech/UofAZ_PIA15039)

Data Collection and Processing

Data collection methods varied by instrument and the features of interest. Flat ground sites, like those used for morphology of patterned ground and surface roughness analyses were most often done with the mobile systems (Optech Maverick and Akhka-R3), although some multi-look tripod scans were done in areas when the mobile systems were already deployed. To collect the mobile data we built a custom backpack mount for the Maverick instrument; the Akhka-R3 is designed to be a permanent backpack-mounted instrument. Ground scans took about 15 minutes each and were done by mapping out and flagging a

The Teledyne Optech Polaris long-range TLS was ruggedness tested on Devon Island and provided data for inaccessible debris gullies and rock outcrops.

50 m x 50 m (or larger) box and traversing back and forth in a grid to saturate the point clouds and minimize shadows. It is from these scans that we achieved the 1–2 cm/pixel highest resolution DEMS. Mobile processing was done using the Distillery software for the Maverick, or by a combination of NovAtel Inertial Explorer, Riegl proprietary softwares, and TerraSolid programs (for processing operator and laser trajectories and point cloud matching for the Akhka-R3). Although some analysis for our purposes could be done directly with the point clouds, georeferenced DEMs were created from .LAS files in ESRI's ArcMap (10.4.1) for integration with other remote-sensing datasets. The major difference between the Maverick and Akhka-R3 instruments was found to be with the laser scanner (Velodyne HDL-32E vs Riegl VUX-1HA, respectively), affecting the corresponding point cloud density, scanning range (~75 m vs ~250 m resp.), and final DEM raster resolution.

For mapping grade (~20 cm/pixel) requirements the Maverick produced excellent ground data. Higher resolution (<2 cm/pixel) near-survey grade measurements were made with the Akhka-R3 (which is a similar system to the commercial ROBIN-precision system from 3D Laser Mapping).

Debris slopes and large rock outcrops were best analyzed by the tripod-mounted systems like Optech Polaris TLS, where we scanned kilometers-long plateau faces with multiple scans. As part of a multi-year study of gully erosion, many of the TLS scans taken during these expeditions were also of areas where we had existing Optech Ilris TLS scans. Polaris TLS scans were processed using ATLAScan software for point cloud merging and georeferencing, and exported to ArcMap for DEMs.

Owing to the longer range of the Riegl VUX-1HA scanner on the Akhka-R3 mobile system, we had great success mapping the same gully systems as the Polaris, with reduced shadowing. This increased coverage came at the expense of increased time and energy (from strenuous hiking) to do these scans, but did provide more uniform resolution. The mobile scanners also allowed us to cover huge areas, allowing us to effectively map entire 'mountains' and, though the course of the expeditions, scanned more than 30 hectares of the arctic. We also tested using the backpack scanners while driving on ATVs (Akhka-R3) and while biking (Maverick). The backpack scanners are top-heavy, which made for very uncomfortable scanning, but the results proved reasonable. The terrain was very rough, so the final point clouds were a bit noisier for the vehicle traverses.

Conclusion

The ultra-high resolution of the newest generation lidars is critical to advancing geomorphologic studies, and for field surveying and mapping in general. Because the technology is so new, and the data returned orders of magnitude higher in resolution than anything previous, scientists like us are just now devising ways to analyze and interpret the data and use it to its fullest potential. Our lidar work from the High-Arctic is helping us understand the interaction of ground-ice and surface topography. We can apply these lessons to Mars geomorphology research and in the search for an accessible water ice resource for future landed-human exploration.

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Dr. Antero Kukko works for the Finnish Geospatial Research Institute as a research manager and is an adjunct professor in the Department of Built Environment, Aalto University, Finland. His research is focused on the development and application of mobile/kinematic laser scanning.

Dr. Catherine Neish is an Assistant Professor of Earth Sciences at the University of Western Ontario. She is an expert in the use of orbital radar observations to study the geology of planetary surfaces, with a particular focus on processes related to impact cratering and volcanism.

Dr. Gordon "Oz" Osinski is an Associate Professor and the NSERC/MDA/CSA/CEMI Industrial Research Chair in Earth and Space Exploration in the Departments of Earth Sciences and Physics and Astronomy at the University of Western Ontario, Canada. He holds a PhD and BSc (Hons) in geology and has spent the past 20 years conducting fieldwork on several continents with a focus on understanding the processes that shape the surface of the Earth and other terrestrial planets.

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