Airborne Laser Scanning for High-Resolution Mapping of Antarctica

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In order to evaluate the potential of airborne laser scanning for topographic mapping in Antarctica and to establish calibration/validation sites for NASA's Ice, Cloud and land Elevation Satellite (ICESat) altimeter mission, NASA, the U.S. National Science Foundation (NSF), and the U.S. Geological Survey (USGS) joined forces to collect high-resolution airborne laser scanning data.

In a two-week campaign during the 2001–2002 austral summer, NASA's Airborne Topographic Mapper (ATM) system was used to collect data over several sites in the McMurdo Sound area of Antarctica (Figure 1a). From the recorded signals, NASA computed laser points and The Ohio State University (OSU) completed the elaborate computation/verification of high-resolution Digital Elevation Models (DEMs) in 2003. This article reports about the DEM generation and some exemplary results from scientists using the geomorphologic information from the DEMs during the 2003–2004 field season.

Airborne Laser Scanning (ALS), also called light detection and ranging, or lidar, combines laser ranging, GPS positioning, and inertial navigation technologies to map the Earth's topography. By depicting the topography with fine detail and unprecedented accuracy (comparable to 1:1,000 map scales), it opens new avenues in Earth science [*Carter et al.*, 2001]. A wide range of geoscience applications, including glaciology, volcanology, geomorphology, geodesy, the investigation of neotectonic processes, and soil mapping, depend on accurate and detailed topographic mapping. Monitoring the mass balance of ice sheets and alpine glaciers [*Krabill et al.*, 2002] and mapping glacial and tectonic geomorphology [*Haugerud et al.*, 2003] are prime examples of using airborne laser scanning methods in polar and formerly glaciated regions.

The most detailed topographic maps of the Ross Sea region of Antarctica prior to the ALS mission were USGS topographic maps at scales of 1:50,000 and 1:250,000. However, these maps lack the spatial resolution and accuracy required for many geomorphologic, hydrologic, and glaciologic applications. This article briefly describes the collection and processing of the ATM airborne laser scanning data, and showcases a few geomorphologic applications that benefit from these new, high-resolution topographic data.

Data Acquisition and Processing

NASA's ATM system measures the range from the aircraft to the ground with a pulsed green laser. The system scans underneath the aircraft at an approximately 15-degree off-nadir angle with a scanner rotation rate of 20 Hz and a laser pulse rate of 5 kHz. The scan pattern is approximately conical. At the nominal flight height of 500 meters above the surface and a speed of 50 m/sec, the laser spot diameter is approximately 1 m and the average density of laser spots was at least one laser point per 2.7 m^2. During the two-week campaign during the 2001–2002 austral summer, about one billion laser points from 20 different sites were collected (Figure 1a).

Data processing is characterized by two distinct phases. In the first phase, NASA computed the latitude, longitude, and elevation for each laser pulse by combining the laser range with differential GPS aircraft position and inertial navigation attitude. This intricate process, using software developed at NASA's Wallops Flight Facility (WFF) and described by *Krabill et al.* [2002], determines the quality of the raw laser point cloud.

The second phase, also known as laser point postprocessing, was carried out at The Ohio State University. The objective is to generate a refined point cloud, free of outliers and systematic errors, giving a faithful representation of the topographic surface.

Outliers were detected by examining the elevations within local neighborhoods, for example, by a median filter. The elimination

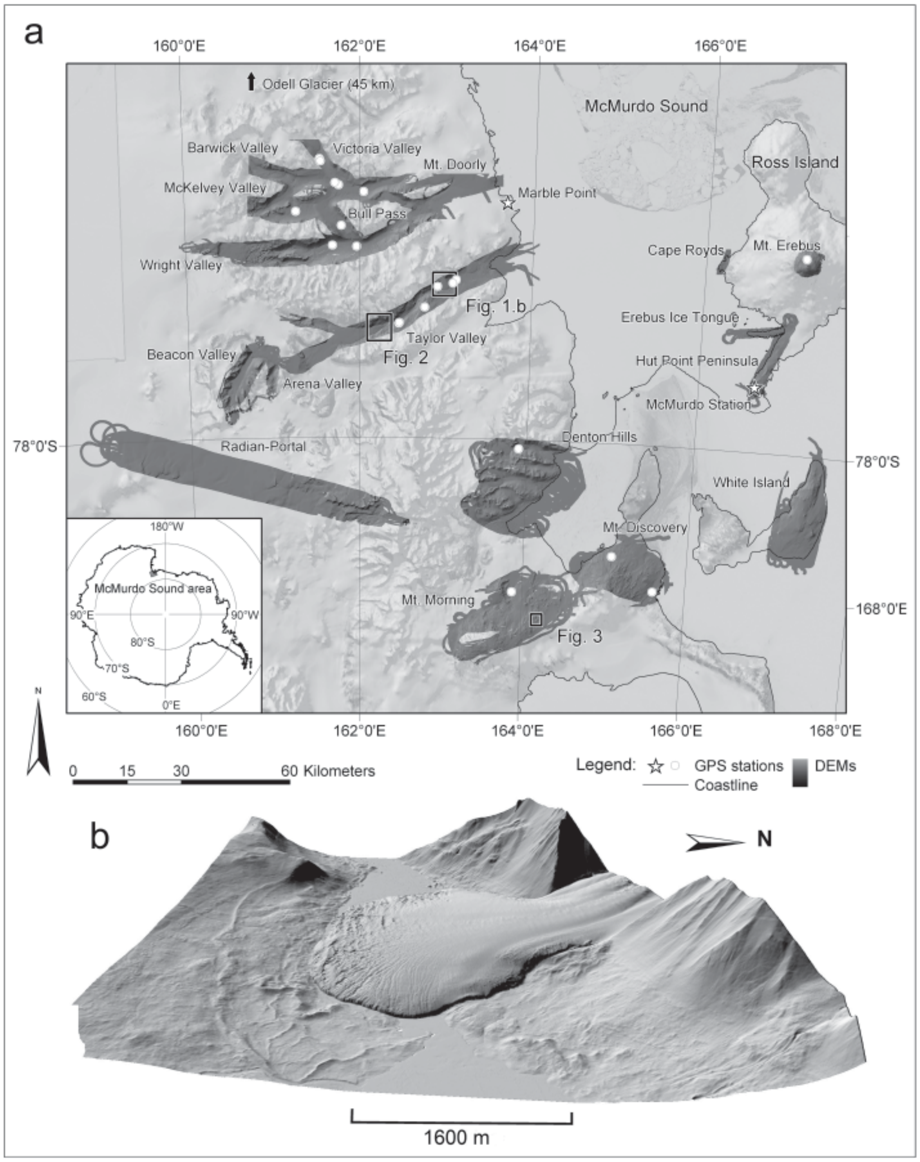

Fig. 1. *An overview of ALS surveys in the McMurdo Sound area. (a) Shaded-relief representation of the new, high-resolution digital elevation models (DEMs) superimposed on Landsat satellite image mosaic (band 2, courtesy of USGS). Stars mark GPS base stations, for aircraft positioning, and circles mark GPS stations for assessing DEM accuracy. The inset is the location of McMurdo Sound in Antarctica. (b) A shaded-relief perspective view of the DEM illustrating its resolution and accuracy, Canada Glacier, Taylor Valley. Meltwater channels, crevasse patterns, and wind-sculpted snow are visible on glacier surface. Other features, beyond the glacier, include an end moraine, moraine ridges and lineations, hummocky drift, and meltwater channels.*

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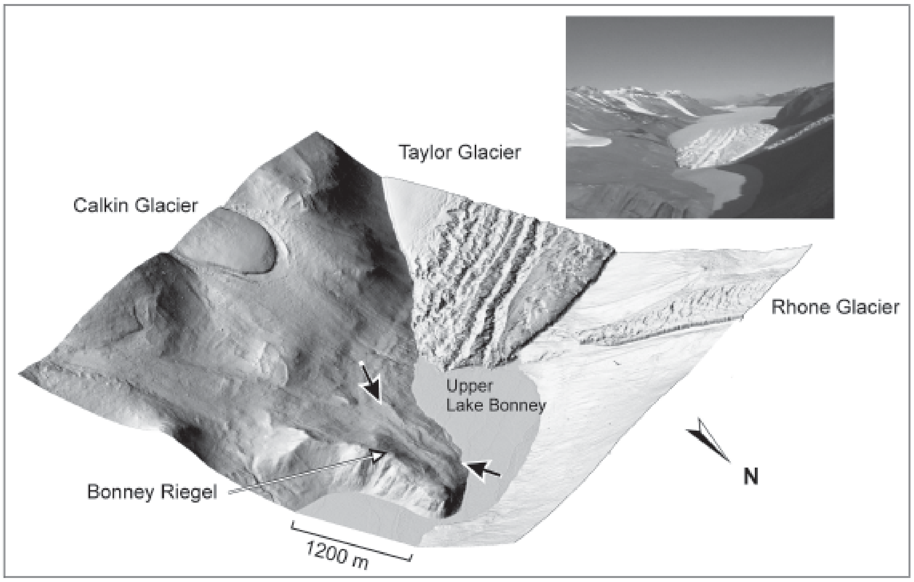

Fig. 2. Mapping meltwater streams and channels, Upper Taylor Valley. Wormherder Creek, a groundwater seep channel first observed in 2001–2002, is marked by arrows on the shaded-relief perspective view of the DEM. Note the topographic expression of other stream channels, for example, downstream of Calkin Glacier and south of Bonney Riegel. Inset courtesy of the McMurdo Dry Valleys Long-Term Ecological Research program.

of systematic errors is more involved. It begins with modeling the most prominent systematic instrument errors followed by determining the model parameters. By minimizing elevation differences of nearby laser points (e.g., in the overlap area of adjacent swaths), the parameters of the error model can be determined, and the raw laser point cloud can be corrected accordingly.

The most intriguing task of post-processing is checking how faithfully the discrete point cloud represents the surface. This process has been combined with the generation of DEMs by introducing a number of plausibility checks. DEMs with a grid spacing of 2 or 4 m were generated for all sites by interpolating the elevations of the grid posts from the irregularly spaced neighboring laser points. Driven by the distribution and density of laser points in the local neighborhood of a grid post, the automatic interpolation scheme adaptively selects a suitable interpolation function, such as fitting planar and higher-order surfaces, and a spatial extent of contributing laser points.

The accuracy of the DEM has been checked with 19 GPS checkpoints, shown in Figure 1a. Precise elevations of the checkpoints were obtained by differential carrier phase processing of data measured by geodetic GPS receivers. The comparison of GPS elevations with interpolated elevations from the neighboring DEM grid posts indicated a root-mean-square error of 0.2 m for the DEMs.

Moreover, the DEMs were inspected with various visualization tools. Due to the superb rendering of topographic surface details, the visual inspection proved to be very effective because even sub-decimeter systematic error patterns become strikingly apparent when using suitable visualization techniques. Noise detected by the visualization was reduced by tuning the parameters of the outlier detection and the interpolation.

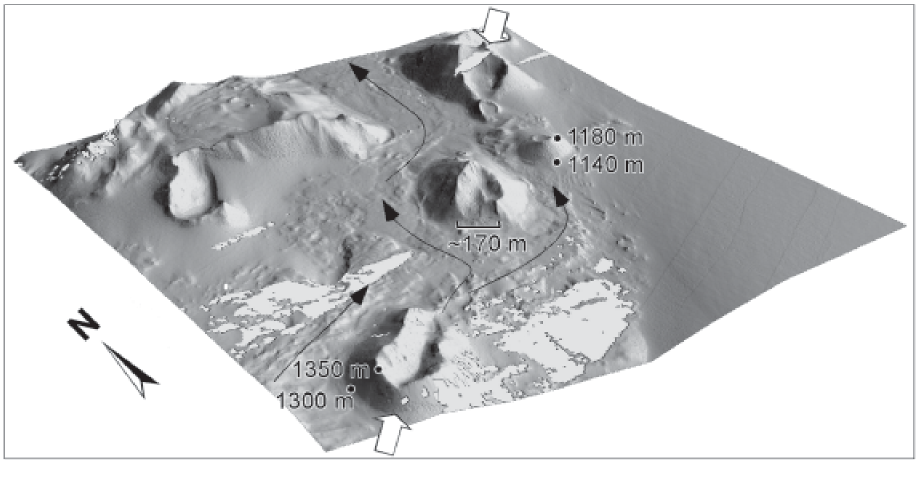

Fig. 3. Mapping volcanic cone alignment and shape parameters. A shaded-relief perspective view of the DEM derived from the NASA Airborne Topographic Mapper survey, showing aligned and elongated volcanic scoria cones and related flows on the north flank of Mount Morning volcano. White arrows demarcate the northeast trending alignment of elongated cones; black arrows delineate lobate volcanic flows from a breached cone rim. White patches are data gaps where laser swaths did not overlap or where laser energy did not reach the surface due to low cloud or fog.

The DEMs and label files as well as detailed site reports are available from USGS's Atlas of Antarctic Research (http://usarc.usgs.gov/antarctic_atlas/).

Periglacial and Glacial Geomorphology and Drainage Patterns

The McMurdo Dry Valleys (Figure 1a) constitute the largest continuous ice-free ground in Antarctica. It is a hyper-arid, cold polar desert, containing a variety of landscapes, including perennially ice covered lakes, ephemeral streams, glaciers, and extensive areas of soil and exposed bedrock.

Geomorphologic mapping and landscape interpretation provide key information toward understanding the climate evolution of the Dry Valleys region, and the new, high-resolution DEMs allow systematic geomorphologic mapping. Figure 1b, depicting the Canada Glacier in the Taylor Valley in Antarctica, provides a glimpse of the geomorphic content of the topographic data. The prominent feature beyond the glacier is a well-defined end moraine, formed 70–120 ka ago during the penultimate interglaciation [*Higgins et al.,* 2000]. Several other moraine ridges and lineations are in front and west of the glacier; meltwater channels occur along the frontal margin, perpendicular to the glacier, and on the distal side of the end moraine.

Production, transport, and accumulation of liquid water are key issues in understanding the McMurdo Dry Valleys ecosystem, as is suggested by the results of the McMurdo Dry Valleys Long-Term Ecological Research (MCM-LTER) program. The MCM-LTER is one of 26 LTER sites now supported by NSF in different habitats to address ecological processes over long periods and across broad scales. The MCM-LTER site was established to assess the impact of climate and climate change on the structure and function of a polar desert ecosystem, primarily in the Taylor Valley.

During the 2001–2002 austral summer, one of the warmest on record, new streams, springs, and seeps were observed in the Taylor Valley by LTER monitoring. Availability of 2-m-resolution DEM data permits regional searching for drainage patterns. For example, *Lyons et al.* [2005] describe flow in a stream channel, later named "Wormherder Creek," south of the west lobe of Lake Bonney in the Taylor Valley. The channel of this creek is clearly visible on the DEM of Taylor Valley (Figure 2), trending northeast along the valley side and then downslope toward the south shore of Lake Bonney from the Bonney Riegel transverse bedrock ridge.

Volcanic Geomorphology

Antarctica contains one of the world's most extensive Cenozoic volcanic provinces. In the McMurdo Sound region, there are large volcanic islands and volcanic cones and lava flows within the Transantarctic Mountains rift-flank uplift [*Kyle*, 1990]. The ATM survey provides the first accurate DEM of the upper part of Mount Erebus, the southernmost active volcano on Earth. Lava flows and volcanic cones are mapped on the north slopes on Mount Morning (Figure 3) and Mount Discovery, on Hut Point Peninsula, and in outcrop and under glacial cover on White Island (Figure 1a).

Volcanic cone alignment and shape parameters, such as the elongation of elliptical cone rims, crater rim height, and crater breach azimuth, are indicators of underlying fractures and hence can be used to determine stress field orientation. A common mapping approach is to establish cone center points and shapes from topographic maps at scales of 1:24,000 or greater. Suitable maps are not available in Antarctica. Satellite imagery can be used to map individual cones, but lacks the detailed spatial resolution and elevation data required for cone analysis.

The DEMs derived from the ATM data are being used to investigate the prominent arrays of volcanic cones on the northern flanks of Mount Morning and Mount Discovery volcanoes to obtain Cenozoic stress data. Figure 3 depicts a number of parasitic cones on the northern slope of Mount Morning, a large Quaternary volcano. Aligned volcanic cones and elongated elliptical cone rims indicate eruption along a northeast trending fissure. The DEM portrays the curving, lobate topography of volcanic flows emanating from breached cone rims.

Results of Geomorphic and Other Applications

The examples shown here demonstrate that DEMs derived from airborne laser scanning data allow delineation of meltwater channels and streams, glacier surfaces, and volcanic topography in unprecedented detail. Additional sites in the region were surveyed to study tectonic geomorphology and geologic control on ice flow. Data were acquired around McMurdo Station, the Cape Royds penguin rookery, and the Odell Glacier blue-ice runway to support logistical operations and environmental studies.

The rich detail of the topographic data has great potential for a multitude of polar applications.

Acknowledgments

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NEWS

In Brief

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Science Academies issue climate change statement Eleven national science academies have issued a joint statement on climate change, in advance of the 6–8 July summit meeting of leaders of the G8 in Perthshire, Scotland.

The statement, issued on 7 June, reads, in part, "The scientific understanding of climate change is now sufficiently clear to justify nations taking prompt action...As the United Nations Framework Convention on Climate Change (UNFCCC) recognizes, a lack of full scientific certainty about some aspects of climate change is not a reason for delaying an immediate response that will, at a reasonable cost, prevent dangerous anthropogenic interference with the climate system."

The statement was issued by the U.S. National Academy of Sciences and the science academies of other G8 nations, Brazil, China, and India.

Changes at USGS Charles "Chip" Groat, director of the U.S. Geological Survey since 1998, resigned from the agency on 17 June to become founding director of The University of Texas at Austin's new Center for International Energy and Environmental Policy.

P. Patrick Leahy, the Survey's associate director for geology, has been named as interim director of USGS. A permanent director must be nominated by U.S. President Bush and confirmed by the U.S. Senate.

—Randy Showstack, Managing Editor

AGU held a 7 June press conference and Capitol Hill briefings to announce its position statement, "NASA: Earth and Space Sciences at Risk." The position statement (published in Eos, 86(23), 7 June 2005), reads in part, "AGU calls for the U.S. Administration, Congress, and NASA to continue their commitment to innovative Earth and space science programs." The statement notes that this commitment is "threatened by new financial demands placed on NASA by the return to human space flight using the space shuttle, finishing the space station, and launching the Moon-Mars initiative." Pictured are (left to right) Eric Barron, chair of the AGU committee that drafted the position statement, and AGU President John Orcutt. Photo by Jonathan Lifland/AGU.