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ACQUISITION OF A TERRESTRIAL LASER SCANNING SYSTEM
FOR
POLAR RESEARCH

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(Optech ILRIS-3D)

Taylor Glacier (left), with visible stream channels, flows from the East Antarctic plateau and terminates in Lake Bonney. (Photo: Dennis Kenley.)

Project Summary: Advances in Terrestrial Laser Scanner (TLS) technology and recent compelling applications of TLS to Earth science research represent new and exciting opportunities for the polar geoscience community. TLS technology is based on Light Distance and Ranging (LiDAR) and is also referred to as ground-based LiDAR or tripod LiDAR. The primary capability of TLS is the generation of high resolution 3-dimensional maps and images of surfaces and objects over scales of meters to kilometers with centimeter or sub-centimeter precision. This allows for high accuracy mapping as well as the determination of surface changes over time via repeated measurements. The incorporation of GPS measurements provides accurate georeferencing of TLS data in an absolute reference frame. The addition of digital photography yields photorealistic 3D images. Moreover, TLS systems are portable and therefore suitable for a wide spectrum of user applications in polar environments. This proposal is for the acquisition of a TLS system and associated digital photography equipment, TLS software and deployment equipment optimized for use in Antarctic and Arctic regions.

This TLS system will be a shared resource managed by the UNAVCO Facility and integrated into UNAVCO's ongoing support for NSF Office of Polar Programs (OPP) projects. Considering the expense of TLS equipment and the expertise needed for successful operation, this approach represents the most cost effective means of making this technology accessible to the OPP research community. Related services currently provided by UNAVCO for OPP projects include pre-season planning, GPS equipment pool, shipping, field support and training, data management and archiving, post-season follow-up, and development work for supporting new applications.

Intellectual Merit: Research projects currently supported by the NSF OPP cover a wide range of disciplines including glaciology, geophysics, geology, volcanology, and biology. All these types of studies will benefit from the capability to acquire TLS imagery. The unique high resolution capability and relative ease of deployment also make TLS a very useful complement to other imaging techniques currently employed in polar regions. These techniques include airborne LiDAR, spaceborne LiDAR, and Synthetic Aperture Radar. UNAVCO supported 40 OPP PI-based science projects in FY2005-2006, including 25 Antarctic and 15 Arctic projects. The availability of a TLS system at UNAVCO optimized for deployment in polar regions will be of significant interest and value to many of these OPP investigators, especially as activities associated with the International Polar Year are developed and implemented.

Broader Impacts: The technical expertise and application experience acquired from this purchase will allow UNAVCO to assist new science users apply TLS technology to their research, substantially lowering the current barriers to entry for this emerging, but complex technology. This project provides the capability and technical foundation for new and exciting interdisciplinary polar research. This work should generate international interest and high visibility during the International Polar Year. Part of a longer-term strategy for TLS will be training of investigators and students in techniques and procedures for data collection and processing as they are developed by the growing TLS community. UNAVCO has a forum for this type of activity through its short course series that includes GPS, strain, and modeling classes conducted by community scientists and UNAVCO staff. UNAVCO provides recruitment of students, registration and logistical support, and evaluation of these short courses. UNAVCO also has an active program to include faculty, students, and post doctoral fellows from both majority and minority populations in these short courses by providing some scholarships. UNAVCO will work in the future with scientists interested in conducting TLS short courses to include participants from underrepresented populations in science, technology, engineering and mathematics (STEM). The engaging and highly accurate visualizations provided by TLS imagery and associated digital photography present a unique opportunity to engage students and polar scientists. Scientists, in addition to being able to make very precise measurements, will bring home a virtual view of Antarctica, a part of the world that most of the public will never see. These new data can be incorporated into future education and outreach materials.

Acquisition of a Terrestrial Laser Scanning System for Polar Research

Introduction

Recent advances in Terrestrial Laser Scanning (TLS) technology (also known as ground-based LiDAR or tripod LiDAR) are opening up the potential of its use in polar applications. These extremely precise and portable terrestrial laser scanning systems, originally designed for engineering applications, have been successfully applied to a range of geoscience investigations including detailed 3-dimensional mapping of quaternary fault scarps, geologic outcrops, hillside drainages, generation of bare-earth topographic maps, and through repeated surveys can image surface changes over time due to motions (such as ice or soil flow), deformation and strain (such as glacial shear and plastic flow or post-seismic earthquake slip), or volume loss or gain (such as soil erosion and ice melting and calving). TLS offers an unprecedented capability to image at centimeter-level resolution 2.5 dimensional surfaces such as topography and fully 3 dimensional shapes such as cultural objects or rock or ice outcrops with overhanging features. TLS is applicable to problems with areal extents at the meter to kilometer scale where detailed analysis is needed. Concurrent GPS measurements can provide accurate georeferencing of the TLS data and absolute 3D coordinates. Coincident high-resolution digital photography allows for the generation of photorealistic 3D images. TLS measurements complement SAR, airborne LiDAR, and spaceborne LiDAR techniques in providing smaller-scale, higher-resolution plots of important areas and in filling in areas inaccesable by these other techniques.

The use of terrestrial laser scanning is part of an ongoing evolution of field data acquisition technologies that is moving toward a fully digital environment that combines equipment for acquiring information in digital and georeferenced format; software that allows seamless transfer, integration, and exploration of data; and online search for and processing of large field and remote sensing datasets generated in or to be used in the field. Ongoing and emerging research by the geoscience community is leading to the realization of this vision of digital field geology that promises to transform both the way we obtain data and the way we analyze, integrate, and interpret results. Some of this vision was articulated in the NSF-sponsored workshop to Identify Ground-Based Digital Acquisition, Analysis, and Visualization Needs of the Geological Science Community (Oldow et al., 2006). Obstacles exist, however, and range from the relatively high cost of field instruments, to barriers arising from the lack of data interoperability between systems, to challenges of using instruments in the field. The latter is perhaps nowhere as evident as in conducting operations in the harsh environments experienced at the polar regions as we will address further in this proposal. The realization of the goals briefly described above is ambitious and will require involvement of a broad community of researchers and extensive development and research efforts to apply these new techniques to a range of important science applications. Here we propose a modest contribution to this effort by purchasing a TLS system that is capable of operating in the polar regions and acquiring the engineering skills to operate it. This pooled resource enables efficient use of expensive equipment and reduces the barriers of entry for new PIs who desire to use this new and exciting technology in their science research.

We propose to acquire one Terrestrial Laser Scanning system for the UNAVCO Office of Polar Programs (OPP) equipment pool. We will conduct several modest tests using this equipment in polar environments as part of existing research efforts, and will make the system, and our acquired engineering expertise, available for future use by the polar community upon request through the OPP Support Information Package (SIP). The SIP is the primary vehicle for requesting support for Antarctic-based projects funded by NSF. We do not request specific logistic field support in this proposal, and any increase in the logistical support requirements of partnering science projects will be identified in the SIP process. The system that we acquire will be a high-precision, long-range, TLS system that is capable of operating in Antarctic field season environmental conditions for use by the polar research community. Given the expense of TLS equipment, a pooled instrument managed as part of UNAVCO OPP operations is the most cost effective means to supply access to the research community. We note that during the austral winter, the TLS will be available for Arctic research, and to the UNAVCO EAR community on a lower priority basis. The TLS instrument, high-resolution digital camera, and commercial processing software, as well as engineering training sessions, will be purchased as part of this grant. Kinematic GPS equipment needed for georeferencing is available from the current UNAVCO OPP equipment pool and staff time for this initial modest development will be part of ongoing UNAVCO OPP support. The TLS system will potentially add a new level of capability to UNAVCO's mission of supporting high precision measurement techniques for Earth sciences applications.

Science Application Examples

Described below are a series of science application examples that could significantly benefit from the use of TLS for detailed 2.5D/3D mapping and with subsequent rescanning could make time-dependant estimates of motion, deformation or surface change. Example topics include investigations of volcanic processes (in particular Mt. Erebus), mapping and changes in ice surfaces, soil stability, geomorphology, active tectonics and technique comparisons with InSAR and LiDAR. During the proposed MRI period, testing at McMurdo Station and a field test in the Dry Valleys will be undertaken as part of core activities in the area. In the subsequent field season, a pilot survey of the Mount Erebus caldera will be done as part of ongoing field work on the volcano being conducted by New Mexico Tech. It is anticipated that work in the other science areas will be generated by new individual PI science proposals to NSF-OPP. The examples below are intended to highlight potential applications, while the specific pilot applications will be based in interest from current field projects.

Volcanic Processes

Mount Erebus (Figure 1) is the southernmost active volcano and has been the target of ongoing NSF-OPP sponsored studies under the leadership of Philip Kyle who directs the Mount Erebus Volcano Observatory (MEVO). MEVO was recently funded for another 4 years to continue a variety of studies and to run a workshop to evaluate future research objectives. A Post-Doc Fellow will be appointed to assist in the operation of the observatory and direct research efforts in understanding conduit processes. A major effort to publish recent observations of Erebus volcano and its activity is underway as a special issue of the Journal of Volcanology and Geothermal Resources which is being edited by Philip Kyle and Dr. Clive Oppenheimer from the University of Cambridge (see the bibliography for selected references). In 2006, 5 Masters students completed their thesis research on Erebus topics bringing a total of over 20 graduate students who have visited and undertaken research work at the volcano. Ongoing work at the volcano includes gas, seismic, petrologic, thermal, and geodetic studies and requires a better understanding of the geometry of the vents inside the summit crater.

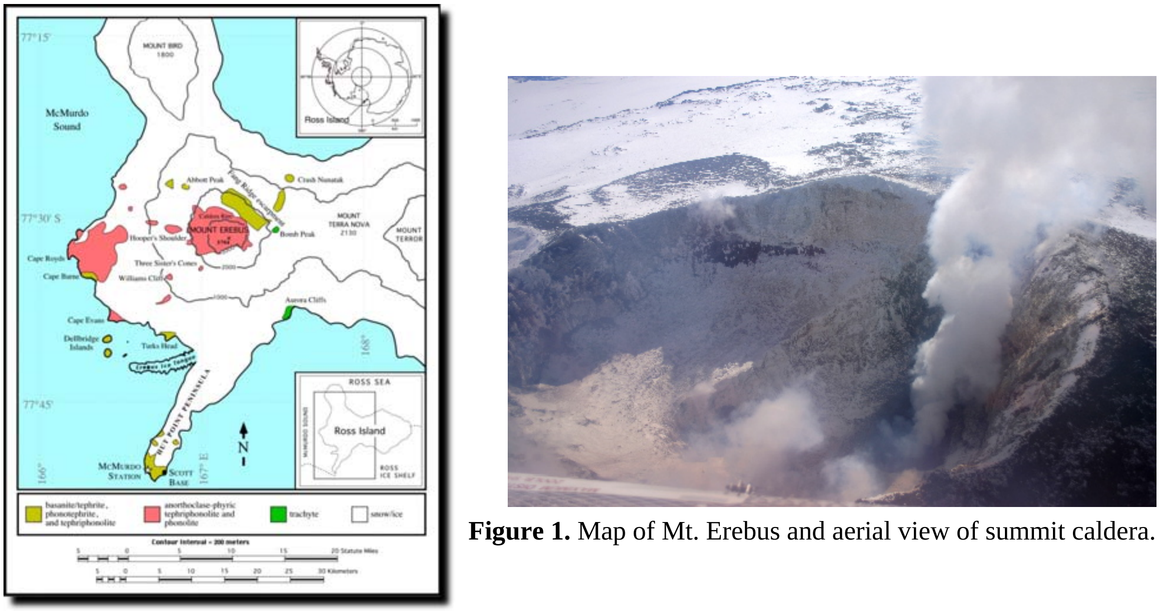


Figure 1. Map of Mt. Erebus and aerial view of summit caldera.

The 3794 meter high Erebus volcano has many unique features, including a convecting lava lake of molten 1000 degree C anorthoclase phonolite magma. Near-vertical walls about 120 meters high drop from the rim of the summit crater to the Main Crater floor. At the north end of this floor is an Inner Crater that drops another 100 meters down to an "Inner Crater" floor. It is within this Inner Crater that we find the lava lake and numerous and sometimes transient vents. These transient features include fumaroles and lava-filled vents (Figure 2) which overflow to form lava flows on the crater floor and, rarely, small lava lakes. The Main Lava Lake is an important source of volcanic gases that are emitted into the Antarctic atmosphere and then widely dispersed over the Antarctic continent. By the very nature of the crater's near-vertical walls, it has been difficult to get a good sense of the geometry and scale of features within this dynamic and ever-changing Inner Crater.

To date, there are no adequate maps of the Inner Crater and very little information on the size, exact shape, and location of the lava lakes and other volcanic features within the crater. Because access to the Inner Crater is extremely difficult and is forbidden by NSF for safety reasons, remote observations are essential. Imaging and mapping of the Inner Crater over the last 30 years using vertical aerial photographs has proved almost impossible due to obscured views from cloud cover and the actual volcanic gas plumes emitted from the lava lake(s). Clear, unrestricted views into the crater are possible under only the few good days of "perfect" conditions. Such perfect conditions occur when the humidity is low and the mainly water-vapor rich gas plume is transparent. Good vertical aerial photos have not yet been taken under such conditions. An aerial LiDAR image was obtained from a flight around the crater in the early 2000's (Csatho, B., T. Schenk, W. Krabill, T. Wilson, W. Lyons, G. McKenzie, C. Hallam, S. Manizade, T. Paulsen (2005), Airborne Laser Scanning for High-Resolution Mapping of Antarctica, Eos Trans. AGU, 86(25), 237, 10.1029/2005EO250002) and does give a view into the Inner Crater; however, the resolution of this image was only 2 meters and parts of it are obscured by plume. Since that image was acquired, there have been remarkable changes within the Inner Crater.

The use of ground-based LiDAR and the associated software tools and technologies will assist greatly and can provide fundamental basic data needed to improve our scientific understanding of Erebus as a volcano. Waiting for the right conditions for imaging becomes much more feasible with ground-based imaging than with the aerial imaging attempted in the past. Because the features in the Inner Crater are so dynamic, updated imagery is needed for current and future studies. For example, MEVO has started to collect thermal images of the lava lake (Calkins et al., 2007) and researchers anticipate calculating heat fluxes from these images. To do so, a good map and knowledge of the size of the lake are critical. Such mapping could readily be accomplished from the Main Crater rim with TLS. Eventual annual rescanning of the volcano's interior will provide researchers with the essential current lava lake dimensions and will track, with high precision, the evolution of the lake and other features within the Inner Crater.

The ability to make high resolution observations of elevations has another important application at Erebus volcano. Recent observation of the lava lake using radar (Gerst et al., 2006; http://www.planet3.de/geo/poster/Alex_Gerst_DGG_2005_Erebus.jpg), Fourier-transform infrared spectroscopy (Oppenheimer and Kyle, 2006), and thermal images made in 2004 and 2005 (Calkins et al., 2007) and in December 2006 (Sawyer, personal communication, 2007) show that the lava lake displays an approximately 10 minute cycle which may be related to convection in the lake. It appears that the lava lake is rising and falling as it convects and degasses (almost as if it is breathing). This is a new phenomenon in volcanology and is clearly related to processes occurring in the conduit that feeds the lava lake. It is therefore essential to measure the surface elevation of the lava lake with a high time resolution. The best way to do this may be with TLS, perhaps operating in a static mode repeatedly taking images of the lava lake. We are not aware of this type of application of TLS at active volcanoes and it will likely require some technology development, which will also enable this use of TLS in other high-rate studies.

Figure 2. Mt. Erebus. TLS surveys of the crater will be conducted from the caldera rim (left). At right is a view of the ongoing lava lake in the Inner Crater.

We recognize that Mt. Erebus, due to its elevation and latitude, presents an extremely challenging environment to operate geophysical instrumentation. The high altitude significantly reduces the ability of helicopters to operate, and most equipment must be carried the final distance to the rim on foot. Both the cold (-30C is common even in mid-summer) and thin air (~14,000 ft pressure altitude) pose both physiological challenges to the operators and physical barriers to instruments designed for warmer conditions. The successful operation of the TLS complex instrumentation at this location is a substantial challenge that will be tackled in year two of the proposed work, after we have gained real-world field experience in less severe Antarctic locations. While challenging, the Mt. Erebus crater presents both an excellent science application and sets a very high standard which will prove that the TLS capability can be environmentally hardened and used for most envisioned Antarctic applications.

Ice Surface and Surface Change

TLS measurements could be readily applied to science problems of ice surfaces morphology and changes, complementing current GPS studies and broadening the scope of problems addressed in polar regions. UNAVCO has supported a number of projects that would benefit from TLS, both in the Antarctic and the Arctic, and within the glacier dynamics, ecological, and operational realms.

Taylor Glacier (Figure 3), an outlet glacier of the East Antarctic Ice Sheet that terminates in Taylor Valley, provides several opportunities to apply TLS measurement to current ice dynamics research. The glacier surface contains a network of melt channels, and their 3-D characterization and evolution over time would contribute to the understanding of glacier meltwater contributions to the Taylor Valley ecosystem (Johnston, Fountain, and Nylen, 2003). Repeated measurements of the vertical sides could quantify the dynamics of dry-land calving (Sniffen, Fountain, Pettit, Hallet, 2005). Mapping surface roughness and topography of this and other Taylor Valley glaciers would also characterize change from many affects including weather, snow-cover, and wind-deposited particles, all of which also affect the glaciers' meltwater contribution to the ecosystem. Also, Taylor Valley lakes, and Lake Bonney in particular, are known to display substantial variations in surface roughness and topography related to year-to-year changes in wind and temperature conditions; detailed 3-D surface mapping would enhance the quantification of these changes and how they relate to the ecosystem freshwater input that could further affect the lake's salinity and biology.

TLS would be of particular benefit in glacier mass balance applications, which contribute directly to our understanding of polar warming. TLS may measure the surface (and volume) change of glaciers with better resolution than what is realistic with on-the-ice GPS observations. Both Commonwealth Glacier in Antarctica—a slow-moving, cold-based glacier for which volume change appears to be stable (Fountain et al., 2006)—and McCall Glacier in Alaska (Figure 4)—a rapidly retreating temperate glacier—may provide excellent cases for applying TLS measurements of the ice surface to the study of glacier mass balance. In both cases, GPS is currently used to measure the thinning of the glaciers, a quantity more difficult to measure than glacier velocity but critical in understanding volume changes. On Commonwealth Glacier, a three-station array of GPS markers is occupied for several weeks each summer season; on McCall Glacier, RTK methods are used to measure the surface elevation of the same points on the glacier twice each summer to determine height changes. In both cases, spatial resolution is extremely limited, whereas TLS would offer a much broader and more precise measurement of surface changes.

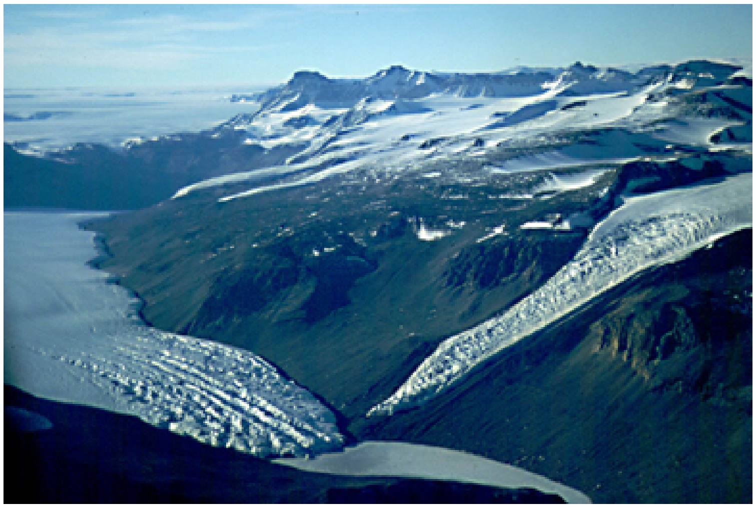


Figure 3. Taylor Glacier (left), with visible stream channels, flows from the East Antarcticplateau and terminates in Lake Bonney. (Photo: Dennis Kenley.)

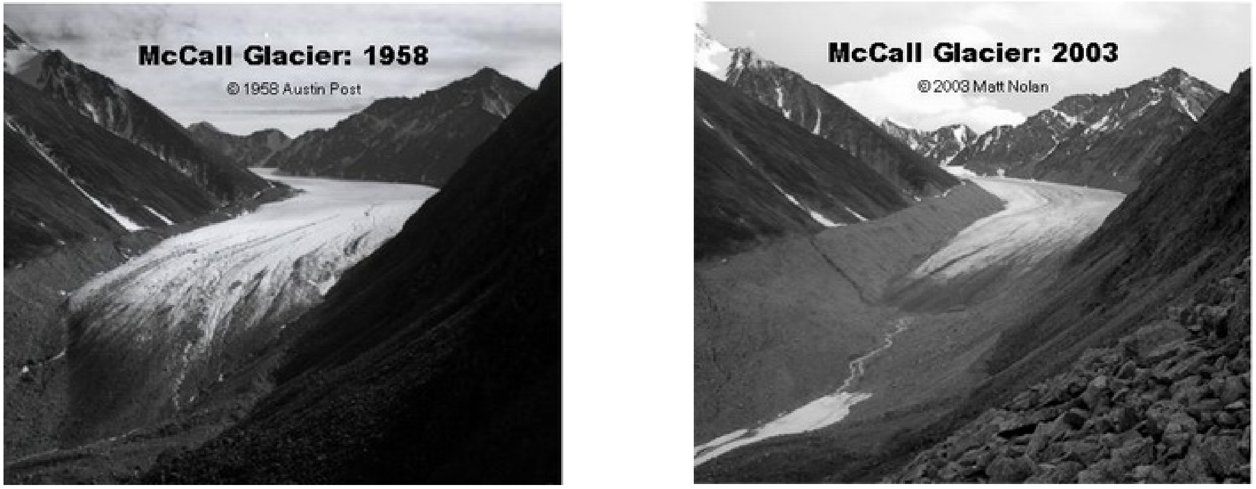


Figure 4. Dramatic changes of the McCall glacier terminus over the past half century. Photos @1958 Austin Post, @2003 Matt Nolan (http://www.uaf.edu/water/faculty/nolan/glaciers/McCall/index.htm).

Operational applications of TLS on ice surfaces include detailed ice runway surface mapping with a resolution that displays the effects of sun and wind, and measuring the total ice deflection field that occurs when the large C-17 transport aircraft is parked on the McMurdo sea-ice apron.

Soil Stability

TLS has the potential to provide an unprecedented measurement capability for soil stability research applications such as measuring the surface displacements in Beacon Valley, which occur due to subsurface ice in the valley floor. This motion has been detected both by GPS and InSAR, and Beacon Valley provides a natural TLS proving ground that would also yield displacements with improved precision and spatial resolution. This work is important for improving the understanding of the dynamics of periglacial processes and long-term surface stability. The study of patterned ground, such as frost polygons and their role in soil transport (Marchant et al., 2002), would also be enhanced by TLS measurements both for surface mapping and for measuring the inter-polygon motion. Arctic soil stability applications include measuring motion of solifluction lobes in the Greenland high-Arctic which would improve understanding of carbon cycling in these features, and mapping and measuring motion of patterned ground to better understand the evolution of periglacial forms (Figure 5).

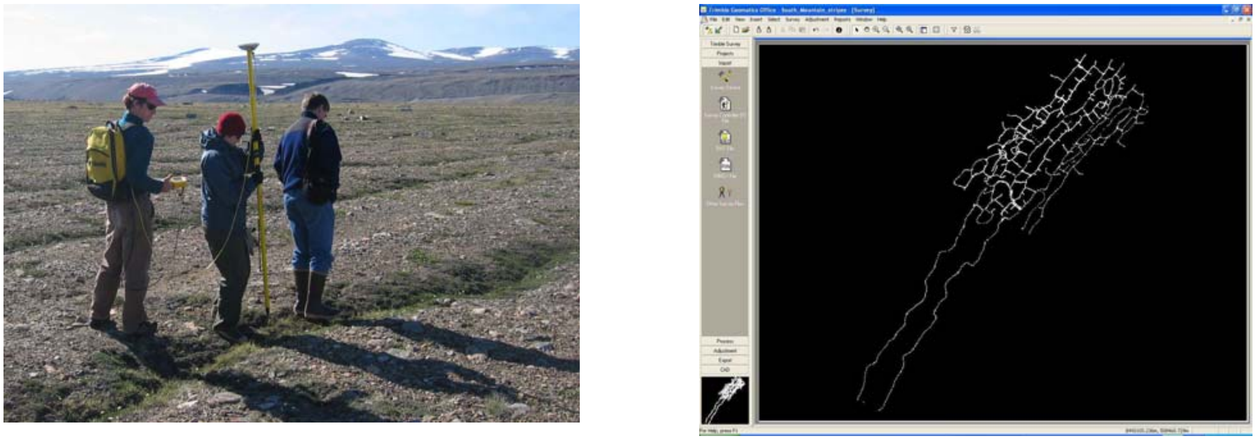


Figure 5. UNAVCO Engineer Beth Bartel taught a field class in kinematic GPS in Greenland in which students (left) mapped patterned ground and used Trimble Geomatics Office software to plot the results (right). TLS in combination with GPS will provide very high resolution 2.5D surface maps and coincident high-resolution digital images of these features. Repeated TLS and GPS surveys will provide precise and arealy extensive data on the motions and causes of these features.

Geomorphology

Other applications within the McMurdo Dry Valleys include precise mapping of stream channels and deltas in Taylor Valley, which would contribute to the active hydrological component of the McMurdo Long Term Ecological Research (LTER) project.

While extremely arid, the Dry Valleys are not devoid of fluvial processes. Glacial runoff provides water to streams and lakes in the valleys. LTER investigations in the Taylor Valley are underway to monitor stream flow and to understand the evolution of the stream basins, deltas, and basin morphology, and ties into measurements of glacial flow and terminus melting and calving (Figure 6). GPS transects can provide only very spatially-limited data of stream basin morphology and change over time. TLS in combination with RTK GPS, however, has the potential to provide very detailed three-dimensional maps of stream basins and allow for analysis and future comparisons to look at change at the cm-level. The scale of the Taylor Valley research area is on the order of a few kms and is a very tractable TLS target. This type of TLS survey work in channel systems has been demonstrated in non-polar areas by Bawden (2005).

The Trans-Antarctic Mountains (TAM) are ideal for studying glacial erosion and stability of mountain landscapes since these polar desert conditions have persisted for millions of years and because the range also has experienced minimal tectonic uplift since late Oligocene time, isolating the erosion signal from any tectonic signal (Kerr, A., Sugden D. E. & M Summerfield, 2000; Huerta & Reusch, 2005). The TAM are an end member that can be used for comparisons with areas such at the Andes where mountain uplift rates are high, and wet conditions result in higher rates of erosion--predominantly fluvial rather that glacial erosion--and dramatically different geomorphology (Montgomery et al, 2001). Digital Elevation

Models (DEMs) of the TAM have been providing an important resource for quantitative analysis of the landforms (Huerta and Reusch, 2005) but are limited by the precision of the DEMs, which is approximately 200 meters. While DEMs of better than 0.5 meter precision will optimally be acquired in the future using airborne LiDAR, TLS surveys can provide key detailed DEMs at the centimeter level where precise quantitative slope and power spectral analysis can be used to distinguish landscapes and dominant sources of erosion.

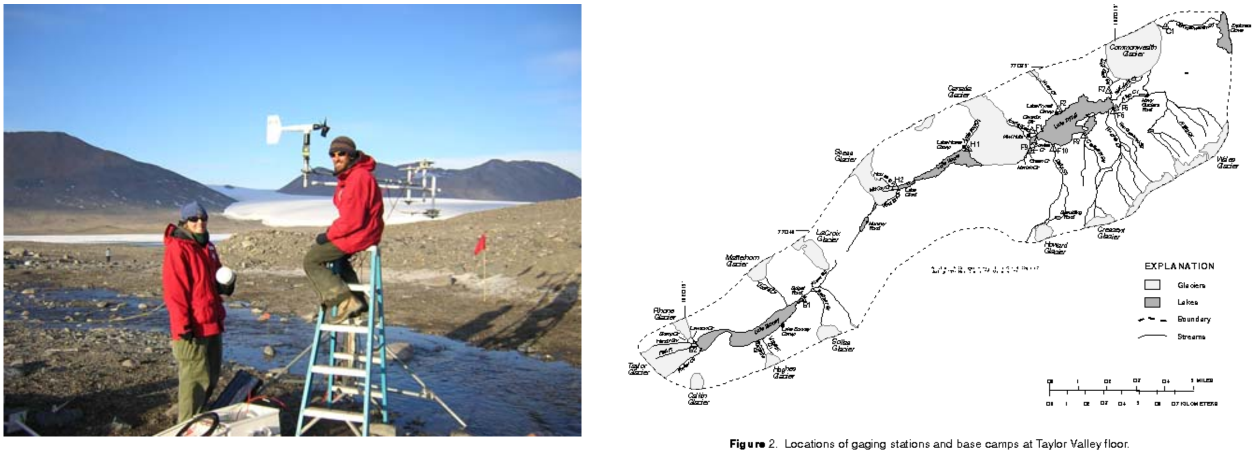


Figure 6. Meterological and hydrological measurements being made in the Dry Valleys by an LTER research team (left). The relatively small km-level scale of features in valleys such at the Taylor Valley make them tractable for high resolution TLS surveying applications (right).

In the Arctic, coastal erosion is a major concern for communities such as Barrow, Alaska, and is another potential target for TLS. Shoreline erosion rates average -0.91 m/year and there is concern that these rates may be accelerating (Manley, 2005). Investigations of coastal processes are underway to study the possible influence of polar warming and decreased sea ice (Manley, 2005). Precise measurements using TLS can complement high-resolution aerial imagery and ground kinematic surveys to provide detailed surface maps of coastal morphology and with repeated precise surveys can improve temporal resolution.

Active Tectonics

The following example, while less applicable to OPP research, demonstrates the power of TLS for earth science applications and highlights the dramatic improvement in resolution of TLS DEMs when compared to conventional 10 m DEMs. The assessment of deformation rates over different time scales taken from a TLS study in the Alvord desert of southeastern Oregon is summarized below.

The need to compare deformation rates over a range of geologic time scales (10^6 to 10 years) arose with the proliferation of GPS-determined velocity fields in continental orogenic belts. The correspondence (or lack thereof) between geodetic and geologic deformation rates carries important implications for the processes associated with strain accumulation and release during the earthquake cycle. Active deformation in the Alvord extensional basin is reflected in the physiography of the region and documented by a system of Pleistocene and Holocene faults that cut late Tertiary volcanic and sedimentary rocks, Quaternary sediments, and shorelines of the ancient pluvial Lake Alvord. TLS imaging of ancient lake shorelines provides the means to measure fault offset at the centimeter scale over time scales of 10^4 to 10^5 years (Oldow et al., 2005). Characterization of fault displacement was not possible using conventional 10 m DEMs, but with the development of 30 cm DEMs based on TLS, resolution was sufficient to measure centimeter-scale displacements of faulted shorelines (Figure 7). A complex history for displacement along the Alvord fault system, newly resolved with TLS and GPS, illustrates order-of-magnitude differences in slip rate between 10^5 and 10^4 year time-scales and substantial spatial variation of fault activity within the basin.

Figure 7. TLS-controlled by GPS in Alvord desert. (left) 10 m digital elevation model of a normal fault cutting ancient lake shorelines. (center) 30 cm TLS-derived digital elevation model of fault-lake shore relations provides details of the structure that were not previously seen, illuminating the complex fault structure and displacement history. (right)

The next example is from post-seismic deformation following the 2004, M6.0 Parkfield earthquake on the San Andreas Fault in central California measured using repeated TLS imagery at two locations along the rupture (Bawden et al., 2005; Bawden et al., 2006). The San Andreas Fault stretches beneath the western side of a bridge into the town of Parkfield. Over the 10 weeks following the mainshock, the supports beneath the bridge moved more than 7 cm while the deck of the bridge moved about 1 cm. After nearly 6 months, the supports moved more than 11 cm and continued to deform portions of the bridge (Figure 8). Capturing deformation in this level of detail and spatial resolution over short time periods would be impossible by any other available method. Using advanced processing techniques including fitting of geometric objects, such as bridge pilings, allows for detection of motion at the mm-level.

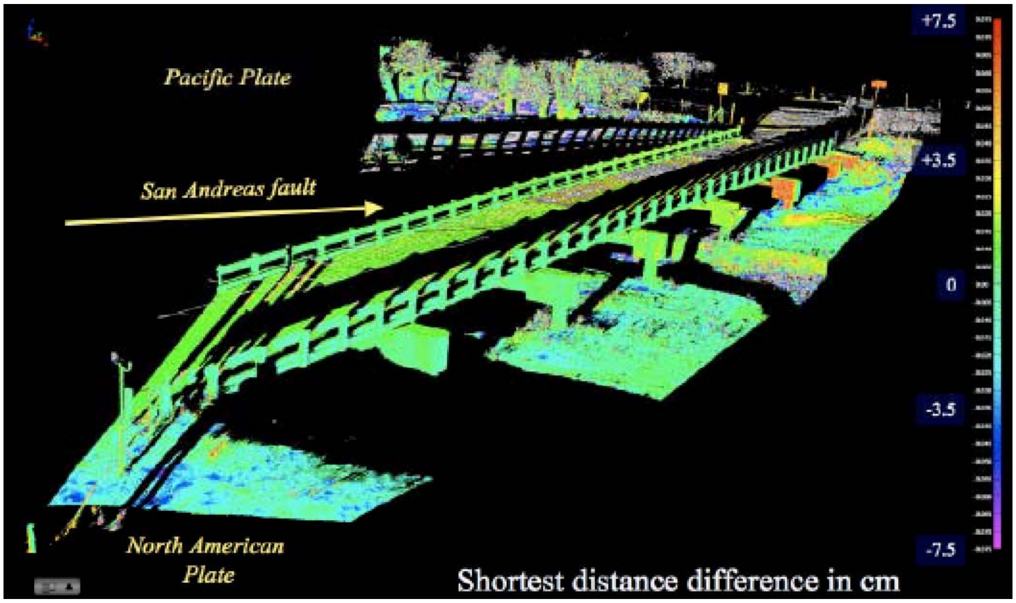


Figure 8. TLS LiDAR imagery of the post seismic deformation field from the 2004 M 6.5 Parkfield earthquake. A bridge that spans the San Andreas fault near the town of Parkfield was scanned about 32 hours after the mainshock and then again 10 weeks later. The imagery was aligned with the North American Plate held fixed and any post seismic motion would be seen as mis-alignments in the scans on the Pacific Plate. Areas that are red and orange moved about 7 cm in the 10-week period. Trees, fence posts, signs, bridge supports, and the ground surface are used to image and measure the post-seismic strain field. This example demonstrates the ability of repeated TLS surveys to capture motion and deformation on a very fine scale using any persistent feature in view.

Integration of TLS with Other Imaging Techniques

The unique high resolution capability and relative ease of deployment make TLS a potentially very useful tool for enhancing, complementing and comparing with other imaging techniques such as airborne laser swath mapping (ALSM, a.k.a. airborne LiDAR), spaceborne LiDAR, and Synthetic Aperture Radar (SAR). In applications to polar research, TLS will provide a means of 1) acquiring very high resolution imagery in order to provide a "closer look" at areas of interest more coarsely imaged by other techniques, 2) acquiring imagery that would "fill in the gaps" when other techniques break down, such as decorrelation of InSAR data, and 3) providing a critical element of calibration and ground-truthing for remotely sensed observations.

While many applications of TLS data integration can be foreseen, we anticipate that the integration of TLS and ALSM imagery will be of particular interest and value to polar investigators. TLS and ALSM are both techniques based on Light Distance and Ranging (LiDAR) technology. TLS complements ALSM in several aspects: 1) area covered, resolution, and precision; 2) cost and accessibility; and 3) the ability to image vertical surfaces. First, in ALSM applications, the instrument is mounted in an aircraft and flown in swaths at a typical altitude of 600 to 1000 m. This results in a typical sampling density of approximately 1-10 points/m^2, and an ability to determine the position of each point with a precision of several centimeters. In contrast, TLS instruments are operated at ranges of a few hundred meters or less, producing point densities of thousands to millions of points/m^2, yielding centimeter to subcentimeter precision. ALSM produces images of broad areas that could not be accomplished with a tripod-mounted instrument, while TLS is best suited for smaller-scale studies. A second difference between TLS and ALSM is the cost and accessibility. While the capitalization costs of both are high, the operating costs of TLS are a fraction of those of ALSM. Without the necessity of maintaining and operating an aircraft, TLS's principal operating cost is travel for the investigator and students. This makes the technology much more accessible for small projects; a few thousand dollars can fund a TLS project. Finally, ALSM scans in the nadir direction at relatively small angles, approx. 20-25° from the vertical, resulting in relatively poor resolution of near-vertical or overhanging surfaces. TLS scans essentially horizontally from a tripod. The geometry provides an ideal platform for imaging steep to vertical surfaces such as fault scarps, cliffs, stream banks, and glacial terminuses.

The integration of TLS and ALSM imagery is a rapidly emerging area of interest within the Earth science community with numerous projects begun or planned (e.g. Bellian et al., 2003; Bruce Marsh, personal comm.; Kenneth Hudnut, personal comm.). Applications of the respective resolution and spatial coverages provided by TLS and ALSM for polar research are myriad with potential targets including ice flow studies, coastal erosion, surface roughness, stream channel characteristics, and so on.

Acquisition of ALSM imagery in polar regions has been successfully demonstrated by numerous projects including surveys in Antarctica such as those in the McMurdo Sound area depicted in Figure 9 (Csatho et al., 2005). The resolution of the ALSM imagery in these particular datasets allows the generation of DEMs with a grid spacing of 2 or 4 meters. TLS imagery could potentially complement ALSM imagery such as this by allowing the generation of much higher resolution DEMs in spatially focused areas. This would provide observational capabilities at a variety of scales for mapping, ground-truthing and change detection through time. TLS data would also be a valuable tool for calibrating ALSM imagery. UNAVCO has previously supported ALSM projects in Antarctica led by J. Mullins, C. Hallam and others by collecting high rate GPS ground control data (e.g. Johns, 2004).

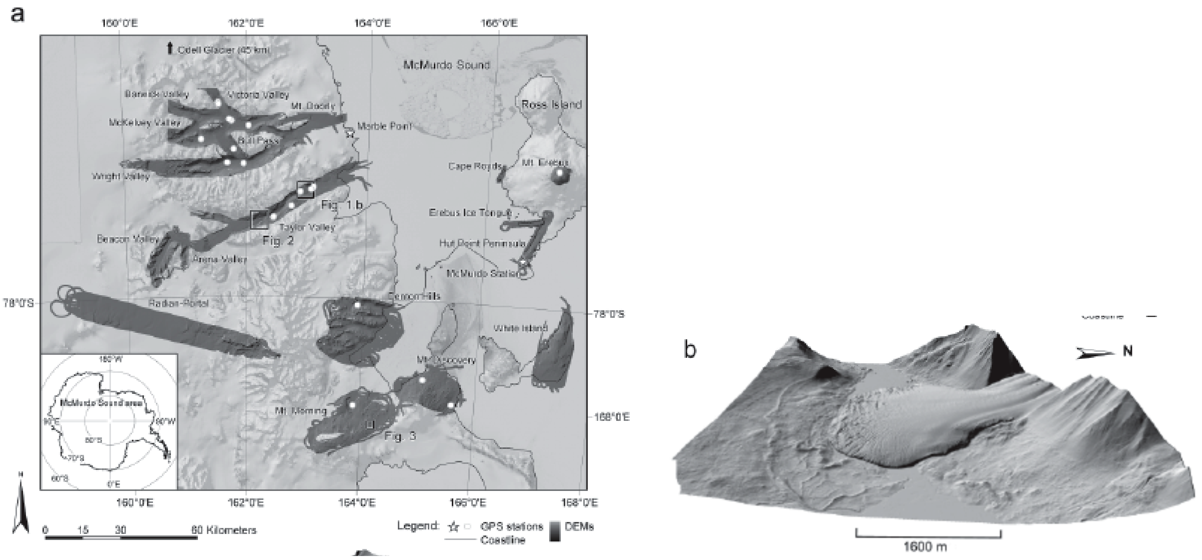


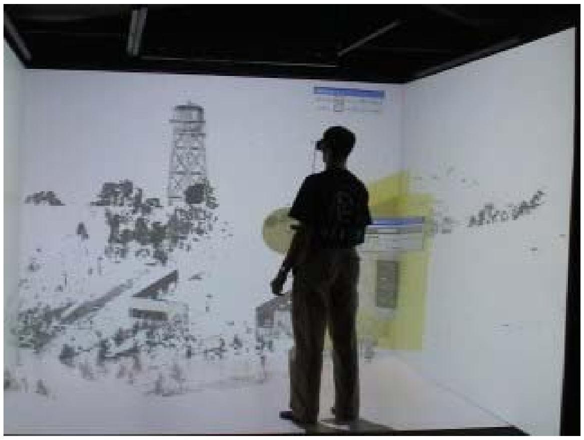
Figure 9. Airborne laser swath mapping (ALSM) surveys in the McMurdo Sound area (source: Csatho et al., 2005). TLS will be a useful tool for acquiring much higher resolution imagery of selected areas covered by ALSM, as well as provide highly detailed ground truthing.

In addition to ALSM imagery, TLS has the potential to complement datasets acquired from imagery techniques that cover even larger scale areas with coarser resolution. Possibilities include applications to spaceborne LiDAR imagery such as that acquired by the Geoscience Laser Altimeter System (GLAS) instrument on NASA's Ice, Cloud and Elevation Satellite (ICESat), as well as spaceborne SAR imagery such as that acquired by the Canadian Space Agency's RADARSAT mission. Additionally, surface changes measured by synthetic aperture radar (InSAR) techniques (e.g. Goldstein et al., 1993) could be calibrated and ground truth provided by TLS imagery.

Education and Outreach Applications

TLS in its most advanced application combines 3D scanning with high resolution digital photography to generate spectacular photorealistic images. Dr. Carlos Aiken and others have pioneered this type of work at the U. of Texas, Dallas. These engaging and yet highly accurate visualizations provide a special opportunity to engage students and scientists in science, technology, engineering and mathematics (STEM). Scientists, in addition to being able to make very precise measurements, bring home a virtual view of Antarctica, a part of the world that most of the public will never see. The capability to generate fully-immersive “3D CAVE” stereo images from TLS/photo data is currently being exploited by developers at the U.C. Davis Keck Center for Active Visualization in the Earth Sciences as shown below (Figure 10). More accessible are GIS tools such as ArcScene that can be shown on more affordable and available “Geowall” stereo systems.

Figure 10. U.C. Davis 3D CAVE showing a TLS scan of the campus.



A more immediate E&O need will be training of investigators and students in TLS technology as techniques and procedures for data collection and processing are developed by the growing TLS community. UNAVCO has a forum for this type of activity through its short course series that includes GPS, strain, and modeling classes conducted by community scientists and UNAVCO staff. UNAVCO provides recruitment of students, registration and logistical support, and evaluation of these short courses. UNAVCO has developed an evaluation tool for the short courses that provides formative feedback to help in improving the manuals and classroom materials and in running subsequent short courses. UNAVCO also has an active program to include faculty, students, and post doctoral fellows from both majority and minority populations in these short courses by providing some scholarships. UNAVCO will work in the future with scientists interested in conducting TLS short coursed to include participants from underrepresented populations in STEM.

TLS System Components

We provide here an overview of the instrumentation and software components required for the acquisition of TLS imagery to support polar investigations. Some components will require new procurements while other components can be provided through the use of existing resources at UNAVCO. The system will be developed, based, and maintained at UNAVCO. The core system will be assembled within the first half year of the project in time for testing at McMurdo in the austral summer field season. An advisory panel made up of members of the polar research and TLS communities will be formed to provide technical recommendations and guidance to UNAVCO.

Hardware

Based on our experiences and those of the larger community, the hardware for the digital field data system should consist of: 1) a TLS that operates at the appropriate range and scan rate; 2) a high-resolution digital camera; 3) handheld and laptop computers to run the TLS; and 4) an RTK GPS system for establishing the real-world coordinates. Ancillary equipment, such as batteries, solar panels, cables, tripods, ruggedized transport cases, etc., to support the system is required and included in the budget, but not discussed in detail here.

TLS System. At the heart of the acquisition system is the TLS. Scanners are capable of producing a 3D topographic model quickly, typically at collection rates of thousands of points per second, capturing about 0.1 km^2 of outcrop area per hour at highest sample density. These instruments produce data in a local coordinate system, similar to traditional surveying measurements, and must be georeferenced with high-accuracy GPS receivers to position independent scan targets or to integrate other sources of data.

The scanning system used as the basis for our budget is the Optech ILRIS-3D (Figure 11). This particular system is currently used by several members of our community and is known to provide the performance characteristics required for the intended applications. We anticipate that special additional provisions will be needed to allow proper system operation in extreme polar environments. The manufacturer has indicated to us that this system has been used previously in Antarctica and that specialized equipment has been developed and is available, such as a custom heating plate for the scanner which extends the operating temperature of the system down to at least -30 degrees C. Typical manufacturer specifications only have a range to 0 degrees C and would not be sufficient to meet Antarctic field needs.

Figure 11. Terrestrial laser scanner (Optech ILRIS-3D) and digital SLR camera (Nikon D2Xs).

High-Resolution Digital Camera. A detailed topographic model produced by TLS forms the foundation for spatial analysis and interpretation. However, geoscientists interact better with actual outcrop or surface imagery when collecting geologic information (as witnessed by the explosion in the use of orthophotography in field geology). We thus propose to use a digital camera to collect images of the area scanned by the TLS. TLS systems are capable of integrating a digital camera directly with data collection so that the image is mapped onto the points collected by the scanner. Other techniques also allow the draping of the image onto topography.

The digital camera system used as the basis for our budget is the Nikon D2Xs digital single lens reflex (SLR) camera or similar and Nikkor 17-55 f/2.8 AF-S DX lens or similar. In addition to a high resolution 12 megapixel CMOS imaging sensor, this camera has many features that make it more appropriate for use in extreme conditions than other cameras, including extensive environmental seals, heavy duty construction, and long battery life. Resources for providing additional custom heating for the camera are budgeted.

Computers. We anticipate that a laptop computer and two handheld PDA control and TLS programming computers (one as an operational spare) are needed to support the TLS system. The laptop computer will be a ruggedized unit, such as a Panasonic Toughbook, and will be used to perform essential field functions such as operating the TLS, gathering geologic information, interfacing with the RTK GPS, etc. The computer will also be used to process the TLS data so that it can be used in the field immediately and to perform additional processing steps and model refinement after data collection is completed.

RTK GPS System. Real time kinematic (RTK) GPS systems are best designed for gathering basic location information in an absolute reference frame. The TLS gathers high-density positional data referenced to a coordinate system local to the scanner position. The data must be transformed into real-world coordinates by establishing the location of the scanner as well a several targets placed within the scanned area. RTK GPS is the most efficient method for doing this, and would provide an additional system for data collection and mapping. An RTK GPS system for use with this TLS will be provided separately by UNAVCO from the existing OPP GPS equipment pool and is not budgeted here.

Software

The hardware listed above will allow users to collect extremely accurate spatial data at unprecedented rates. These data, however, must undergo several processing steps to be useful, including georeferencing, combination of point data sets, and generation of topographic surfaces.

TLS Software. TLS manufacturers typically provide acquisition software with capabilities to automatically scan and register targets, and manage data files. Once the data are collected, they form an array of thousands to billions of individual points (point cloud) that represents the imaged surface. This mass of data can only be handled initially by specialized software. This is particularly critical when aligning multiple independent scans of an area or merging scans into a single surface model.

The TLS system used as the model for our budget, the Optech ILRIS-3D, includes one portable license for QT Modeler, an automated alignment software package, as part the standard system. QT Modeler is a basic tool that can be used to visualize data, interactively and automatically align multiple fields of scanned data, save aligned data to a wide variety of formats, and other essential TLS functions.

Based on the recommendations of the community, we also plan to use Innovmetric Polyworks software for advanced TLS applications. Polyworks is more versatile and powerful than QT Modeler and allows advanced point cloud processing and supports a wide variety of scanners. It has modules that allow the aligning of huge point clouds, the creation of triangulated meshes from the points, the efficient editing and clean-up of the models, and georeferencing with the use of control points. The INSPECT module for modeling is expensive but allows effective modeling of simple geometric features especially important for control monuments used for monitoring. The Polyworks software is also required for integration of digital photography with point clouds.

GPS and GIS Software. GPS software is provided by the RTK GPS manufacturers/vendors and is available with UNAVCO pool RTK systems. This software offers the capabilities needed to process the data and establish accurate positions. GPS and TLS data can be exported to GIS to provide higher precision base maps; investigators are already using GIS to view, integrate and perform analysis on a wide range of field data. Because of its wide use, great power, and continued updating and support, we intend to use ESRI ArcGIS software as the GIS. This will work with the topographic models and images as well as provide substantial capabilities in a 2.5D environment. ESRI ArcGIS software will be provided separately by UNAVCO.

Project Plan

Year 1. The proposed equipment acquisition plan and associated field tests are scheduled around the Antarctic field season. The initial steps are to develop specifications for the equipment, put the purchase out for bid, evaluate capabilities, determine the best system for the project and acquire the necessary hardware and software. Concurrently, a UNAVCO Polar Field engineer will get training in the operation of the equipment and software. Training will be provided by the TLS manufacturer and travel and class costs are budgeted for this in this proposal. The goal is to ship the TLS system down to Antarctica by November, 2007, in time for the UNAVCO engineer to conduct field tests at McMurdo in January, 2008. A field test in the McMurdo Dry Valleys will also be conducted. A first survey of Mt. Erbebus may be attempted, but will be subject to available time, logistics and weather constraints. Such a survey will only be considered in the first field season if sufficient experience is gained with TLS tests in more benign conditions. The UNAVCO field engineering team and Phil Kyle, the head of the New Mexico Tech Mt. Erebus project, will do this evaluation.

Year 2. The bulk of the TLS system acquisition will be completed in the first year of the project. It is anticipated, however, that system modifications will be needed after the experience of the first field season and time is allotted to make these modifications during the second year of the project. The main Mt. Erebus crater scan will be planned for the 2008-2009 Antarctic field season. The use of the TLS for other PI projects will be offered and subject to logistics, demand, and constraints based on experiences gained from the first year.

Data Products and Archiving. UNAVCO has a long established archive and data management system for GPS data collected by community investigators from continuously operating stations and episodic campaign surveys including data from OPP projects (see Facilities Section of this proposal). UNAVCO also has recently become responsible for the WiNSAR archive, as well as the InSAR and ALSM archives for GeoEarthScope. In the future, similar systems will be needed to handle field data from TLS surveys. Initially, however, we will archive all TLS and related data acquired in simple UNAVCO "repository mode". Data will be publicly available to anyone as soon as they are archived unless there are time exclusions approved by NSF program managers. Collected data will include field data and metadata from the range of data sources (TLS point cloud, high-resolution digital photos, field notes, GPS, and other ancillary project information). Higher-level products such as user-generated aligned, georeferenced, meshed surfaces and digital geologic map databases will include not only high-resolution 2.5-D digital elevation maps, but also detailed geologic mapping in GIS formats, and associated metadata.

Long Term Plans

This proposal provides the OPP research community some initial TLS capability through the acquisition of a new low-temperature, high range TLS system that is capable of operating in harsh polar regions. It also provides the training of a UNAVCO field engineer who will be available to help users with their fieldwork and standard processing. This is only the initial capability, however, and the long-term vision of the fledgling TLS geoscience community includes development of equipment, software, procedures, instruction, and data management and sophisticated processing using emerging CyberInfrastructure that will allow the scientific user to effectively collect TLS and associated digital geologic, ecologic and other metadata, in order to process and analyze the large volumes of data that will be collected in a simple seamless manner (Oldow, 2006; and the UNAVCO collaborative "*INTERFACE: INTERdisciplinary alliance for digital Field data ACquistion and Exploration facility for cm-scale, 3D digital field geology" proposal*" http://www.unavco.org/pubs_reports/proposals/2006/LidarProposalforWeb.pdf). These and other developments underway from projects like GEON will be emerging as the broader TLS community grows. Our proposal helps reduce barriers to effective use of TLS by providing equipment and expertise and will enable broader use of this exciting cutting-edge technology by the polar science research community. These tools, the high precision 3D "snapshots" of the dynamic and ever-changing polar landscapes will be a legacy of the project that will have long term impact on the way fieldwork is conducted and will be of keen interest to the international community as the International Polar Year unfolds.

NSF Cooperative Agreement EAR-031760, "Support of UNAVCO Community and Facility Activities", 7/1/2003–9/30/2007, $13,009,777. PIs: William H. Prescott, Charles M. Meertens.

UNAVCO, Inc. is a non-profit membership-governed organization that supports and promotes Earth science by advancing high-precision geodetic and strain techniques such as the Global Positioning System (GPS), InSAR, and borehole strain and tiltmeters. There are currently over 90 UNAVCO Members and Associated Members. Through this core NSF Cooperative Agreement, UNAVCO operates a Facility that provides engineering, an equipment pool, data, archiving, and information technology support to NSF (EAR and OPP) - and NASA-funded peer-reviewed projects. The Facility supports peer-reviewed science projects of research investigators who individually, or in large collaborative projects (such as the *PBO Nucleus* or even larger, multi-disciplinary, multi-agency *EarthScope MREFC*) study Earthquake processes, mantle properties, active magmatic systems, plate boundary zone deformation, intraplate deformation and glacial isostatic adjustment, global geodesy and plate tectonics, global change, and polar processes. Additionally, UNAVCO supports UNAVCO Community activities including bi-annual national Science Workshops, short courses at the Facility, external advisory committee meetings, and support for education and outreach activities. Detailed reports of UNAVCO Facility activities and PI projects supported can be found at: http://www.unavco.org/pubs_reports/reports/reports.html.

Results of Prior NSF-Support:
The most recent NSF grants relevant to this proposal are the on-going:
NSF ANT-0538414: "Mount Erebus Volcano Observatory II (MEVO II): Surveillance, models, impacts and outreach", 9/1/06-10/30/10. $800,145, PI – P. Kyle, Co-PI R. Aster
NSF OPP-0229305: "Mount Erebus Volcano Observatory and Laboratory (MEVOL)", 5/1/03-4/30/07, $532,758. PI – P. Kyle, Co-PI R. Aster
and the now complete Major Research Instrumentation (MRI) grant:
NSF OPP-0116577: "Development of integrated seismic, geodetic and volcanic gas surveillance instrumentation for volcanic research", 9/1/01 -08/30/04, $148,363. PI – P. Kyle, Co-PI R. Aster.

The MRI Integrated Surveillance Instrumentation (ISI) initiative was collaboration between NMT, UNAVCO, and Guralp Systems. The project designed and built 6 integrated real-time telemetered volcano geophysical observatories. Five were deployed on Erebus (Aster et al., 2004) and one near the Socorro magma body in New Mexico. All stations are currently operational although issues of power have not been completely resolved and the Erebus stations have down periods during the dark Antarctic winter when calm weather restricts wind generator operations. The stations are providing a continuous stream of data from a high dynamic range seismometer and digitizer, continuous dual frequency GPS, weather stations, and electronic state of health sensors. Additional instrumentation at selected sites includes infrasound microphones, IR thermometer, and tiltmeters. The data are telemetered to McMurdo Station using spread-spectrum 900 MHz Freewave radios, and can be viewed in near real-time at the Mount Erebus Volcano Observatory (MEVO) web page. Seismic and GPS data are made freely available to the international research community through the IRIS Data Management System and UNAVCO. MEVO webpage. (http://www.ees.nmt.edu/Geop/Erebus/erebus.html)

The Mt. Erebus Volcano Observatory was established to monitor volcanic activity and to continue surveillance of the seismicity and gas emissions of Mt. Erebus, the most active volcano in Antarctica. The MEVOL and MEVO II grants are the principal source of Erebus associated research and field funding. The grants providing support for annual field work at Erebus in which 10+ people usually participate. A large number of students have and are being supported by these grants (in the last 6 months 6 M.S. students have completed their research on Erebus and a PhD and 3 M.S. students are currently in progress). Research has also resulted in a wide range of publications and presentations (Aster, 2005; Aster et al., 2004a, b; Bartel et al., 2004; Esser et al., 2004a,b; Gret et al., 2003, 2005; Johnson and Aster, 2003,2005; Johnson et al., 2004a, b, 2005; Kelly et al., 2004; Kyle et al., 2004; Oppenheimer et al., 2004b; Sweeney et al., 2004; and Ryan and Kyle, 2004). (See the MEVO web-site for details of the above listed references). At this time a special issue of the Journal of Volcanology and Geothermal Research (JVGR) on Erebus volcano is in preparation. Six paper which were supported by these grants have been submitted (for a selection of these papers see the Bio/vitae of Philip Kyle) and there are currently 4 more in preparation and these will be submitted for publication to JVGR over the next 6 weeks.

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