A Facility Plan for Polar Seismic and Geodetic Science:

Meeting Community Needs Through IRIS and UNAVCO Polar Services

This plan has been coordinated by the Polar Networks Science Committee, a joint IRIS/UNAVCO committee, with input from a broad cross-section of the polar seismic and geodetic science community.

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ACRONYMS

AES: Antarctic Earth Science Program, OPP, NSF
AGAP: Antarctica's Gamburtsev Province Project
ANET: The Antarctic component of POLENET
DMC: IRIS Data Management Center
EAR: Earth Science Division, NSF
FDSN: International Federation of Digital Seismograph Networks
GAMSEIS: Gamburtsev Antarctic Mountains Seismic Experiment
GLISN: Greenland Ice Sheet Monitoring Network
GNET: The Greenland component of POLENET
GPS: Global Positioning System
GSN: Global Seismographic Network
IDA: Project IDA (International Deployment of Accelerometers), Scripps Institution of Oceanography
IRIS: Incorporated Research Institutions for Seismology
LARISSA: Larsen Ice Shelf System Initiative
MRI: Major Research Instrumentation Program, NSF
NSF: National Science Foundation
OPP: Office of Polar Programs, NSF
PASSCAL: Program for Array Seismic Studies of the Continental Lithosphere, IRIS
PIC: PASSCAL Instrument Center
PNSC: Polar Networks Science Committee
POLENET: Polar Earth Observing Network
TAMSEIS: Transantarctic Mountains Seismic Experiment
UNAVCO: University NAVSTAR Consortium
USAP: U.S. Antarctic Program
USGS: U.S. Geological Survey
WISSARD: Whillans Ice Stream Subglacial Access Research Drilling Project

Executive SUMMARY

Seismological and geodetic research in polar regions addressing interdisciplinary science questions of global significance is leading to major scientific breakthroughs and technological advances, most notably in the areas of ice sheet dynamics and mass balance, solid earth structure and deep earth processes. The research has direct relevance to societal needs and NSF Office of Polar Programs (OPP) research goals, and relies heavily on support from the IRIS and UNAVCO facilities.

The importance of polar seismic and geodetic science has led, over the past decade, to rapid growth in the number of NSF-sponsored projects utilizing seismic, GPS and other remote sensing equipment. The scope of the research goes well beyond the fields of geodesy and seismology, and includes climatology, meteorology, glaciology, geomorphology, volcanology, and space physics. The rapid growth in the number and variety of polar projects impacting the IRIS and UNAVCO facilities, the frequency of requests to NSF for project support, and the need to coordinate field logistics across many projects is creating significant challenges for all involved, including principal investigators, facility staff, and NSF program managers.

To address these challenges, a workshop titled "Building a Framework for Facility Support for Polar Seismic and Geodetic Science" was held September 8-9, 2011 at the National Science Foundation. The workshop brought a broad cross-section of the science community that utilizes UNAVCO and IRIS facility support together with NSF program managers and staff from UNAVCO and IRIS. A primary need identified during the workshop was for a facility plan to guide the growth and management of the UNAVCO and IRIS polar facilities over the next 5 to 10 years.

This facility plan, developed from the workshop outcomes, describes the services currently provided by IRIS and UNAVCO for supporting polar seismic and geodetic projects, documents the strengths of the facilities, identifies major challenges facing them, especially from increasing community demands, and gives guidance for the management and growth of the facilities through a number of recommendations. Summaries of major challenges and cross-referenced recommendations are provided below. The recommendations, grouped into three broad categories (technology, management and governance), specify ways to strengthen and expand the services provided to the community, improve governance, and enhance data recovery and quality through harnessing technological advances.

Major Challenges

1) Fulfilling commitments to PI projects with delivery of high quality, fully tested instrumentation systems while simultaneously maintaining large networks and pursuing technological developments and propagating them to existing stations is difficult with existing staffing levels.

2) Lengthy field seasons in demanding conditions put a great deal of strain on facility staff.

3) Maintaining adequate and flexible inventories to support a wide range of Arctic and Antarctic projects without having to constantly ship equipment between polar regions is challenging.

4) There are technological challenges to supporting both short- and long-term, continuous acquisition of seismic and GPS data from polar regions. These include developing sustainable solutions for power and communications, improving environmental enclosures, and cold-hardening equipment.

5) To improve station operations, synergies in engineering design and logistics sharing are needed to maximize the efficient use of limited resources. IRIS and UNAVCO have established an effective collaboration through jointly developing power and communications technologies, and in planning support for polar projects. Finding time and resources to support these collaborations and for the cross training of IRIS and UNAVCO staff is a challenge.

6) The lack of a sufficiently large on-ice facility to test, repair and stage field instrumentation and prepare equipment for remote deployments creates inefficiencies and increases work loads.

7) For UNAVCO, maintaining technical competence in GPS survey methods and data processing techniques is challenging due to time constraints brought about by heavy field season support.

8) Obsolescence of the GPS receiver pool is a major issue. The Trimble NetRS receiver, which makes up 100% of the remote ANET, GNET, and LARISSA network sites, is aging, out of production, and will only become less reliable over time.

9) For IRIS, a larger, dedicated polar instrument pool is needed to meet community demands.

10) The complexities of supporting polar projects are challenging existing governance and management structures within IRIS.

Management Recommendations Common to IRIS and UNAVCO:

• Maintain capable and well trained staff to meet the existing and future demands of NSF-OPP funded projects requiring facility support (Challenges 1, 2 and 7)

• Increase the level of cross training within and between the facilities (Challenge 5)

• Engage with NSF to improve workspace for testing, staging and long-term storage of equipment at field logistics hubs, in particular McMurdo Station, Antarctica (Challenge 6)

• Establish closer coordination between NSF, the facilities, and the investigators in project planing through project award to more effectively schedule supported projects and make available the resources needed for implementation in the field (Challenges 1 to 4)

• Foster and support collaborations with other polar science communities to advance mutual goals of improved data return and quality from multi-sensor stations (Challenges 5 and 6)

• Together with relevant governance bodies, develop a mechanism for evaluating the needs and possible transition plans for current PI-led stations to long-term facility-operated stations (Challenges 1 to 5 and 10)

UNAVCO- Specific Recommendations

Technology:

• Improve and formalize the infrastructure associated with terrestrial laser scanning operations (Challenges 1 to 3)

• Improve designs for continuous stations to eliminate single-point failures and increase reliability (Challenges 3 and 4)

• Identify the next GPS receiver for continuous use in polar regions (Challenge 8)

Management:

• Support enough terrestrial laser scanning (TLS) instruments to meet community demand (Challenge 3)

• Create enhanced training materials and make them available as a resource to the community (Challenges 1 and 7)

• Together with relevant governance bodies, coordinate the development and implementation of a plan for longer-term GPS station operation and maintenance for ANET/POLENET (Challenges 1 to 4)

• Maintain a limited stock of equipment and spare parts for strategic, long-lead time items (Challenge 3)

• Maintain a state-of-the-art pool of equipment suitable for polar applications, with separate sets of equipment for Antarctic and Arctic use (Challenge 3)

• Establish a strategic plan for battery replacement at long-term continuous stations (Challenge 4)

Governance:

• Continue the effective governance provided by the current cross-cutting nature of UNAVCO's committee structure

IRIS-Specific Recommendations

Technology:

• Improve communications systems to allow retrieval of full bandwidth data from all stations (Challenge 4)

• Improve data quality, including improvement of on-site quality control capabilities (Challenge 4)

• Improve the cold specifications for polar instrumentation, and work with equipment manufacturers on implementation (Challenge 4)

• Improve integration of system components with state-of-health output to communication systems (Challenge 4)

• Develop enclosures for cold, wet environments (Challenge 4)

Management:

• Continue coordination with OPP on operations of existing Antarctic GSN stations (Challenges 1 to 4)

• Improve collaborations with equipment manufacturers to enable on-demand ordering of system components, and to improve the cold tolerance, ease of use, and ruggedness of sensors and data-acquisition systems and enable use with non-seismic sensors (Challenge 4)

• Together with relevant governance bodies, coordinate the development and implementation of a plan for longer-term seismic station operation and maintenance for GLISN and ANET/POLENET (Challenge 1 to 4)

• Work with the community to develop and implement a plan for establishing and maintaining a dedicated polar instrument pool that is large enough to meet community needs (Challenge 9)

• Develop capabilities for effective evaluation of emerging technologies (Challenge 4)

Governance:

• Establish a governance structure for polar activities to (1) provide an effective, efficient, and transparent forum for community input directly to the polar staff; and (2) provide commensurate budget oversight (Challenge 10)

• Establish a management structure for polar activities to (1) define a clear transmission path for community input; (2) provide a well-defined and open path for communication between NSF and IRIS polar staff; and (3) provide a clear decision-making pathway for polar activities (Challenge 10)

1.0 INTRODUCTION

Over the past decade there has been rapid growth in the number of NSF-sponsored projects in polar regions utilizing seismic, GPS and other remote sensing equipment provided and maintained by the IRIS and UNAVCO facilities (see text in blue and gray boxes). The nature of the science projects utilizing equipment and support from IRIS and UNAVCO span Earth structure and processes from the inner core to the ionosphere, and include the fields of geodesy, seismology, climatology, meteorology, glaciology, geomorphology, volcanology, and space physics. The rapid growth in the number and variety of polar projects impacting the IRIS and UNAVCO facilities, the many requests to NSF for support of these projects, as well as the need to support and coordinate field logistics for the projects, have created many challenges for all stakeholders, including Principal Investigators, facility support staff, and NSF program managers.

Consequently, a workshop titled "Building a Framework for Facility Support for Polar Seismic and Geodetic Science" was convened and held September 8-9, 2011, bringing together a broad cross-section of the science community that utilizes UNAVCO and IRIS facility support with NSF program managers and staff from UNAVCO and IRIS to discuss future community needs for polar facility support. A primary need identified was for a facility plan to guide the growth and management of the UNAVCO and IRIS polar facilities over the next 5 to 10 years.

The workshop was held at the National Science Foundation in Arlington, VA and was attended by over 40 scientists, and staff members from NSF, IRIS, and UNAVCO. This document serves both as the workshop report and the facility plan for polar seismic and geodetic science; it links to and builds from several related reports, most notably the Autonomous Polar Observing Systems Workshop (APOS) Report, and the National Academy of Sciences Report on Antarctic Science.

The plan reflects the organization of the workshop, the nature of the deliberations by the attendees, and the resulting recommendations. Background information on the growth of the IRIS and UNAVCO facilities are provided in this chapter. In Chapter 2 a brief review is provided of the first-order science questions driving the growth in use of polar seismic and geodetic facilities. Chapters 3 and 4 focus on the services provided by the IRIS and UNAVCO facilities, and Chapter 5 explores strategies and pathways for collaboration, creating efficiencies in facility support, and improving governance.

1.1 Growth of IRIS and UNAVCO polar facilities

The growth in facility support from IRIS and UNAVCO over the past decade for seismic and geodetic science is illustrated in Figures 1-3. For UNAVCO, the growth has come mainly from projects deploying GPS equipment over multiple years recording continuously (cGPS), in addition to a significant ramp up in the number of projects using other kinds of equipment, such as ground based LiDAR (Fig 1a). In comparison, the number of projects making campaign measurements in polar environments has fluctuated from year to year. The increase in demand for UNAVCO facility

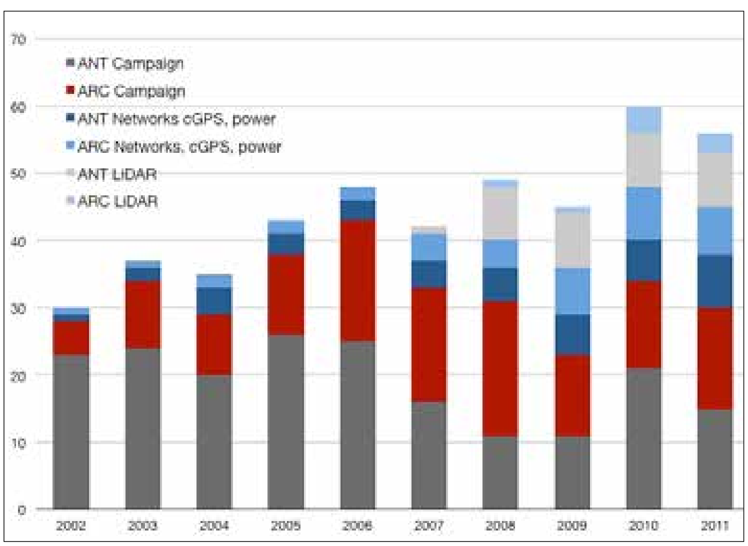

Fig 1a: UNAVCO Polar projects by type and program showing recent growth in LiDAR, networks, cGPS applications, and power systems.

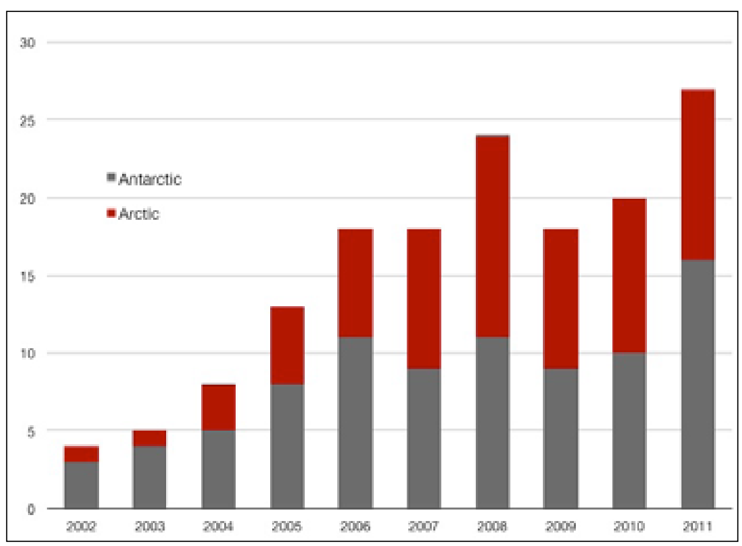

Fig 1b: IRIS PASSCAL supported experiments showing the growth in the number of experiments active each year by region.

support is also reflected in the growth of the GPS receivers in the UNAVCO equipment pool available for polar projects (Fig 2a) and the cGPS data holdings in the UNAVCO data archive (Fig 3a). The growth in both these areas is occurring as a result of an increased number of Arctic and Antarctic projects supported by NSF.

There are similar trends in the growth of polar projects receiving IRIS support. In particular, there has been rapid growth in the number of projects supported in the Arctic (Fig 1b). The growth in the polar seismic equipment pool and data archived from polar projects mirrors the trends for GPS equipment and data (Figs 2b, 3b).

Because of the increased demand for polar facility support, staffing at IRIS and UNAVCO over the past decade has also evolved to address the needs of the polar science community. The impact on facility staff has been significant, and in many instances the facilities have had to utilize core facility staff to support polar projects because of high pressure to get projects into the field on short notice.

1.2 Polar facility support

With the establishment of UNAVCO as an independent, non-profit, university-governed consortium in 2002, OPP Arctic and Antarctic funding began to be included in UNAVCO's 2003-2007 core Cooperative Agreement. The UNAVCO polar support program grew in scope with the increasing number of funded PI projects and the availability of a growing number of polar field-worthy campaign units in the UNAVCO pool.

For IRIS, funding for equipment has been provided primarily through MRI awards to develop power and communication systems for autonomous stations and to purchase cold-equipped seismometers and data loggers. Supplemental awards to the IRIS Cooperative Agreement in response to the needs of funded PI projects have provided additional funding for equipment. IRIS staff has also been supported through supplements to the IRIS Cooperative Agreement, and the amount of support has increased over the past decade as the number of polar seismic projects has grown.

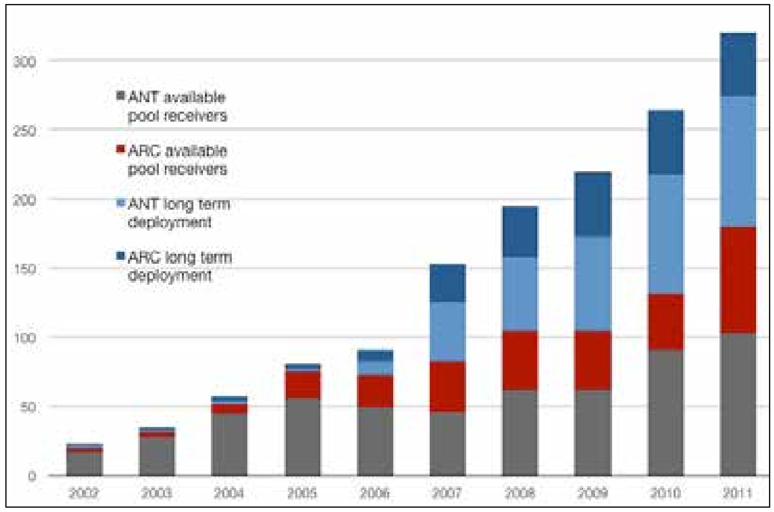

Fig 2a: Growth of UNAVCO Polar GPS receiver pool in response to larger campaign projects, long-term deployments, and networks.

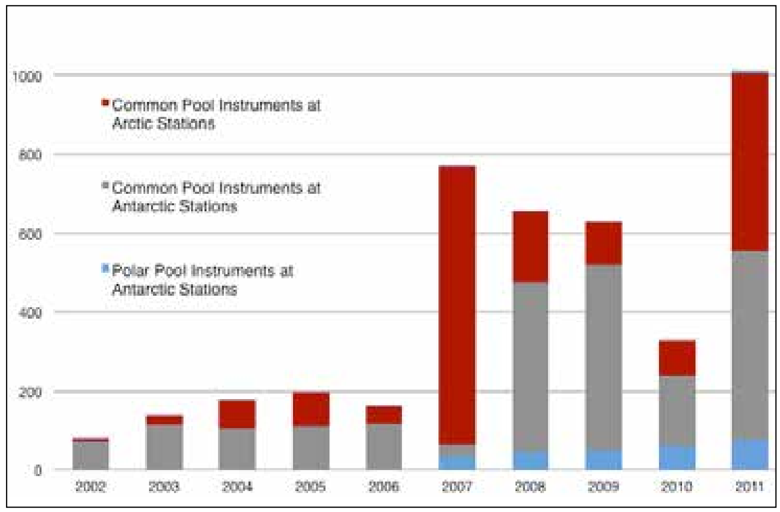

Fig 2b: Polar seismic stations supported with PASSCAL equipment, illustrating the growth in use of equipment and the reliance on common pool instruments to meet project demand.

1.3 Trends in facility support needed for polar seismic and geodetic science

Trends in facility support are driven primarily by technological advances, science problems that require ever-longer field deployments with increasing numbers of sensors, and pressures to reduce the logistical costs of deep field installations. The needs to harness technological advances for improving data quality and quantity, the latency of data, and reducing overall costs are discussed in the APOS report and go well beyond just the polar seismic and geodetic communities. As new and better power systems, communication devices and sensors become available, the science community relies on the facilities to keep abreast of relevant technological advances and to lead efforts to utilize those technologies for advancing the community's ability for making field observations.

Field deployments in some of the coldest, wettest and most remote polar regions are required to address many first-order polar science questions, and notable successes in obtaining important new data sets from such regions over the past few years have whetted the appetite of the science community to tackle even more challenging problems. Consequently, the science community will likely continue to ask the facilities for ever-larger amounts of support, keeping pace with, if not exceeding, the ramp up in demands placed on the facilities by the science community over the past decade.

Balancing the need for larger field deployments over longer periods of time with the availability of polar logistical support has also helped to push the science community and facilities to seek creative and flexible ways to reduce the size and weight of equipment and power systems, as well as modes of equipment installation and transportation. This balancing act places increased pressure on the schedules of facility staff, in addition to other field team members, and often means that the efficient use of staff time is compromised for the sake of making other pieces of the logistical puzzle fit together. As larger and more logistically challenging projects are developed by the science community, facility staff will likely experience increased demands on their time, their abilities to harness technological advances for reducing equipment size and weight, and their abilities to design and implement new methods of transporting and installing equipment.

1.4 Long-range projections of facility needs

Given the rapid growth in the use of IRIS and UNAVCO facility support by the polar seismic and geodetic community over the past decade, what is in store for the next 5 to 10 years? From a community perspective, simply maintaining the current capabilities of IRIS and UNAVCO to support field-based polar projects will not enable the facilities to provide the level of support required for undertaking new, groundbreaking field projects. Projections that factor in the many broad, interdisciplinary, and society-relevant science goals of the community indicate that the demand for facility support over the next decade will grow at a similar rate to the past five years. It is clear that only with substantial growth in facility support can the "remote sensing" of the polar regions using seismological and geodetic methods achieve its full potential for advancing the frontier of polar science.

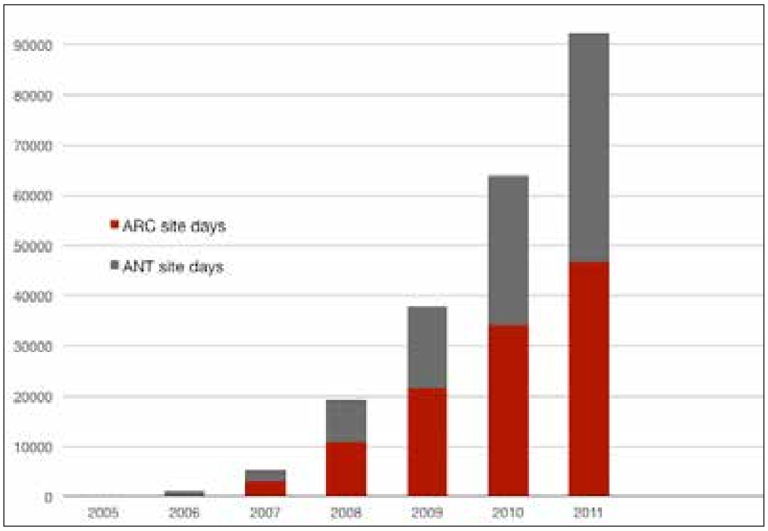

Fig 3a: UNAVCO polar data holdings showing nearly 100,000 site days in the archive (Dec 2011).

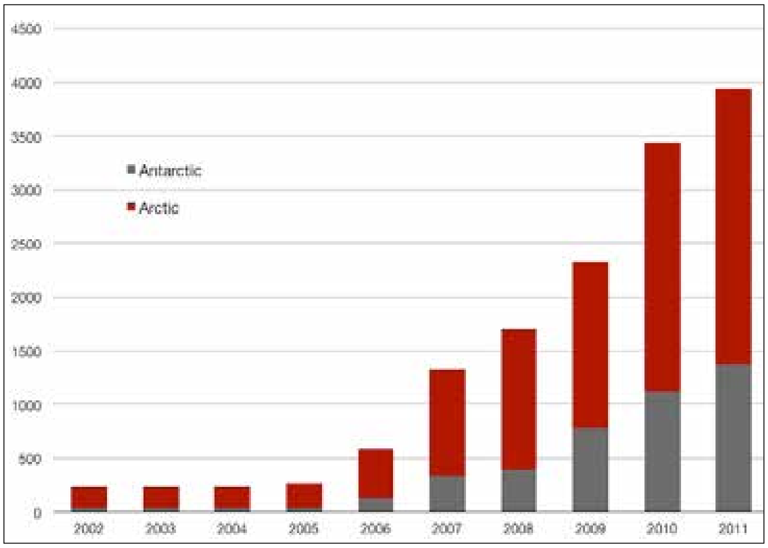

Fig 3b: Cumulative SEED data archived at IRIS DMC (GB) from polar stations.

IRIS

Founded in 1984 with support from the National Science Foundation, IRIS is a consortium of over 100 US universities dedicated to the operation of science facilities for the acquisition, management, and distribution of seismological data. IRIS programs contribute to scholarly research, education, earthquake hazard mitigation, and verification of the Comprehensive Nuclear-Test-Ban Treaty.

The mission of the IRIS Consortium, its members, and affiliates is to:

- Facilitate and conduct geophysical investigations of seismic sources and Earth properties using seismic and other geophysical methods.
- Promote exchange of geophysical data and knowledge, through use of standards for network operations, data formats, and exchange protocols, and through pursuing policies of free and unrestricted data access.
- Foster cooperation among IRIS members, affiliates, and other organizations in order to advance geophysical research and convey benefits from geophysical progress to all of humanity.

IRIS membership comprises virtually all US universities with research programs in seismology, and includes a growing number of Educational Affiliates, US Affiliates, and Foreign Affiliates. IRIS management is provided through a small staff headquartered in Washington, DC. IRIS facilities are primarily operated through member universities and in cooperation with the U.S. Geological Survey. A governing Board of Directors and several standing committees provide IRIS with advice on managing its facilities. Support for IRIS comes from the National Science Foundation (including the EAR Instrumentation and Facilities Program, EarthScope, and Office of Polar Programs), other federal agencies, universities, and private foundations.

UNAVCO, a non-profit university-governed consortium, facilitates geoscience research and education using geodesy. UNAVCO is a university-governed consortium, an organization that is uniquely positioned to advance and support geodesy community science goals. In addition to over 100 US academic members, UNAVCO supports more than 65 organizations at home and abroad as associate members that share UNAVCO's mission and benefit from its programs and services. Before incorporation in 2001, UNAVCO existed under different organizational umbrellas for nearly two decades as the University Navstar Consortium, then primarily serving geophysicists and geodesists who study tectonic deformation using high-precision GPS technology.

Over the last decade, UNAVCO's scope has expanded significantly, serving new science communities - including those who focus on the deformation of ice, the Earth's response to ground water, sea level, and other aspects of the hydrosphere, and renewed interest in imaging the structure of the atmosphere. At the same time, the toolbox available to the science community and supported by UNAVCO has expanded to include many new geodetic tools: advancing GPS towards mm-level global GPS geodesy and to streaming high rate observations; borehole strain meters and seismometers, expanded geodetic imaging using LiDAR (Light Detection and Ranging) for Airborne Laser Swath Mapping, InSAR (Interferometric Synthetic Aperture Radar), and Terrestrial Laser Scanning, web services and cyberinfrastructure. At the same time, GPS is finding applications in a frequency range that used to be the sole province of seismology, as GPS moves from one solution per day to one solution per second, with high precision. These changes are part of a conscious strategy to meet the future needs of the science community.

The UNAVCO Facility located in Boulder, Colorado provides science support through community coordination, field engineering, data services, technology innovation, and instrument testing, acquisition, and deployment. Further, it supports state-of-the-art global geodetic infrastructure that is developed and operated through international collaborations.

GNET cGPS Station "DGJG" in East Greenland -*Courtesy UNAVCO.*

2.0 From sea level rise and ice sheet stability to solid earth structure and dynamics

POLAR SEISMIC & GEODETIC SCIENCE

The importance of understanding the Arctic's and Antarctic's (past, current and future) role in global sea level change, climate, and tectonic activity is stressed in both the NSF/OPP research goals and the National Research Council report "Future of Science Opportunities in Antarctica and the Southern Oceans" (National Academies Press, 2011). NSF funding for these research goals through PI-led projects and facility support produces both scientific discoveries and technology advances. In this research endeavor, IRIS and UNAVCO play an increasingly important role in supporting the geodetic and seismological polar communities; with their support, scientists are uniquely positioned to obtain the key datasets required for making major scientific breakthroughs in areas of ice sheet dynamics and mass balance, solid earth structure and deep earth processes.

IRIS and UNAVCO, working together with the science community, support polar field operations using their respective science observation platforms. As noted in Chapter 1, progress optimizing these observing platforms for polar conditions has generated growth in the scientific demand for IRIS and UNAVCO support. Much of this demand comes from interdisciplinary projects, which now dominate platform use, and results directly from NSF support of interdisciplinary research addressing high priority questions. Continued support in instrument development and availability at the facilities will be needed to keep pace with scientific demands.

Below, we outline some of the scientific motivations for continued support of seismic and geodetic investigations in the polar regions. Because this is a "facility plan", as opposed to a "science plan", a comprehensive science overview is not provided. Instead, a concise overview is provided of major science topics driving the communities' expanding interests in polar geodetic and seismological projects, along with some of the most compelling science questions.

2.1 Ice mass balance and sea-level

Sea level rise from enhanced ice sheet discharge (including ablation, melt, and dynamic losses) is one of the largest and most immediate potential consequences of climate warming. Complete melting of the Greenland and Antarctic ice sheets would raise eustatic sea level by over 60 m; however, the societal and economic effects of even a modest rise in sea level would be disastrous, given that 600 million people live in coastal zones. Sea level change over the last century, due to thermal expansion of the ocean, enhanced river discharge, reservoir impoundment, diminishing glaciers, permafrost, and aquifer pumping has led to a net global sea-level increase of 1.7 ± 0.5 mm/yr (IPCC, 2007). The rate of sea level rise increased to 3.1 ± 0.7 mm/yr in the past decade, and is projected to increase to ~4 mm/yr by 2090 under current emissions scenarios (IPCC, 2007).

Current eustatic sea level rise predictions are based on the balance between snow accumulation and surface/basal melting and steady rates of ice discharge and do not include changes in the dynamic response of outlet glaciers due to climate warming (IPCC, 2007). Until recently, it was thought that large ice sheets respond slowly (timescales of >1000 years) to changes in external forcings (such as air and ocean temperature, precipitation, and sea level), but recent observations of large climate-driven changes in ice sheet and glacier flow speeds in parts of Greenland and Antarctica point to the need to include in sea level predictions processes that operate much more rapidly.

In the past decade, ice sheets and mountain glaciers have discharged ice into the ocean at a faster rate than at any other time in at least the past 50 yrs. This increase in mass loss is mainly attributed to changes in the flow configuration of several large outlet glaciers in Antarctica and Greenland. During the past ten years Greenland's rate of ice loss has increased five-fold over that measured for the last decade (1992-2002), and Antarctica's has increased by about 50%. A review of all of the space data is now complete (Shepherd et al., 2012). However, the present-day rates of change for mountain glaciers are large (~50% Greenland; Jacob et al., 2012), and thus enhanced understanding of these smaller glacier systems is also essential.

Observations of thinning, retreat, and acceleration are detected along most glaciers with negative mass balances, but the detailed mechanisms triggering these changes are not well known. In several cases, changes in glacier flow dynamics are a response to climate-related perturbations at the seaward margin, although other mechanisms related to changes in subglacial hydrology might also play a role in speed increases. Obtaining a better understanding of sea level change requires improved ice-sheet-ocean-atmospheric models and observations. Improved knowledge of the physics governing outlet glacier flow and accumulation variability is absolutely essential for improving the input-output method of ice sheet mass balance.

Our understanding of glacier dynamics and mass balance has improved in the last decade, largely due to new altimetry, radar interferometric and gravimetric satellites and advances in ground-based technology. The most direct method of determining mass changes over Greenland

and Antarctica is by space gravimetry. However, for this method to contribute to our understanding of sea level change, knowledge of vertical movements of bedrock in Antarctica and Greenland arising from viscoelastic and tectonic processes is required. Translating the uncertainties caused by the lack of observational control on models of post-glacial rebound (the most probable source dominating large vertical motions) to sea level sourcing produces an uncertainty of roughly 0.2 to 0.3 mm/yr. Modeling of ongoing isostatic processes also requires knowledge of the upper mantle structure.

Consequently, GPS and seismic observations, made possible by advances in field-deployment technology, are critical for improving our understanding of ice sheet dynamics (Fig 4-6). These advances include:

- The ability to collect continuous ground-based data year-round (improved power generation through wind and solar), enabling more remote deployments.
- Remote site management and maintenance (improved iridium capabilities), with significant, although limited, data return.
- Data acquisition at high-risk glacier margins (improved enclosure design and instruments, reduced cost and better data transmission).
- Coupled seismic and GPS observations.

Indeed, on-ice GPS and seismic measurements provide the temporal and spatial resolution necessary for addressing many of the key science questions. For example, GPS datasets can be used to investigate the response of ice flow to tidal forcings, weather variability, subglacial and supraglacial water drainage patterns and iceberg calving events. These high-temporal resolution studies of ice flow response are critical for obtaining new constraints on glacier processes and ice sheet models. Seismic observations of glacier events are now being used for a range of relevant studies including: investigating ice shelf stability and disintegration mechanisms, assessing tidal impacts on tidewater glaciers, the dynamic behaviors of icebergs, characterizing sub-ice water flow and the transport of water through and beneath glaciers (Figs 5).

Key science questions include:

- What are the dynamics of flow, accumulation and mass balance from daily to decadal time scales, and their impacts on sea level?
- How do we better correct space gravimetry for isostatic rock motions to obtain ice sheet mass balance?
- What are the timescales of variability in ice dynamics (seconds to decades) and how do these impact long-term mass balance?
- How do atmosphere and ocean dynamics impact the stability of ice shelves and floating ice tongues?
- What is the relationship between the configuration of floating ice (ice shelf, ice tongue, sea ice-iceberg mélange) and glacier flow speed and other dynamics?
- What is the role of the basal boundary in the flow of glaciers and ice sheets?
- How important is the formation and discharge of subglacial lakes in ice sheet dynamics and mass balance?

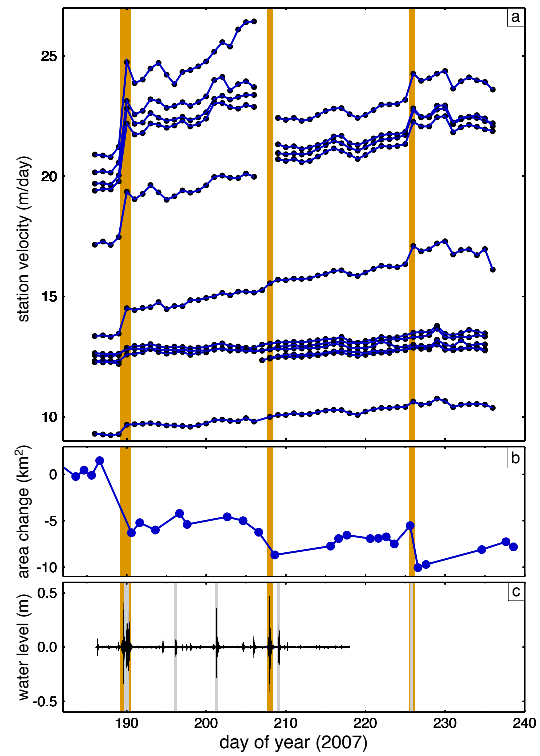

Figure 4: The relationship between glacier velocity at GPS stations (~2 km to 20 km from the glacier front) and calving events (from Nettles et al., 2008). (a) Average daily along-flow speed for GPS stations on the surface of Helheim Glacier. The slower-moving GPS instruments are ~20 km from the glacier front; the faster-moving units are within a few km of the terminus. (b) Cumulative change in glacier area with respect to total area on day 180. Rapid changes towards more negative values indicate large calving events (derived from MODIS imagery). (c) Short-period (200–4000 s) variations in water height near the end of the Helheim fjord with respect to the average water level. Times of large glacial earthquakes are indicated by orange bars (three events on days 189–190, one event on day 207, one event on day 225); smaller earthquakes are indicated by gray bars. The earthquakes correspond to large calving events.

Figure 5: On the Left: Gordon Hamilton deploys a kinematic GPS receiver on Helheim Glacier, East Greenland (photo courtesy of Greenpeace). On the right: co-located seismic- GPS installation in the fast flow zone of Yahtse Glacier, Alaska.

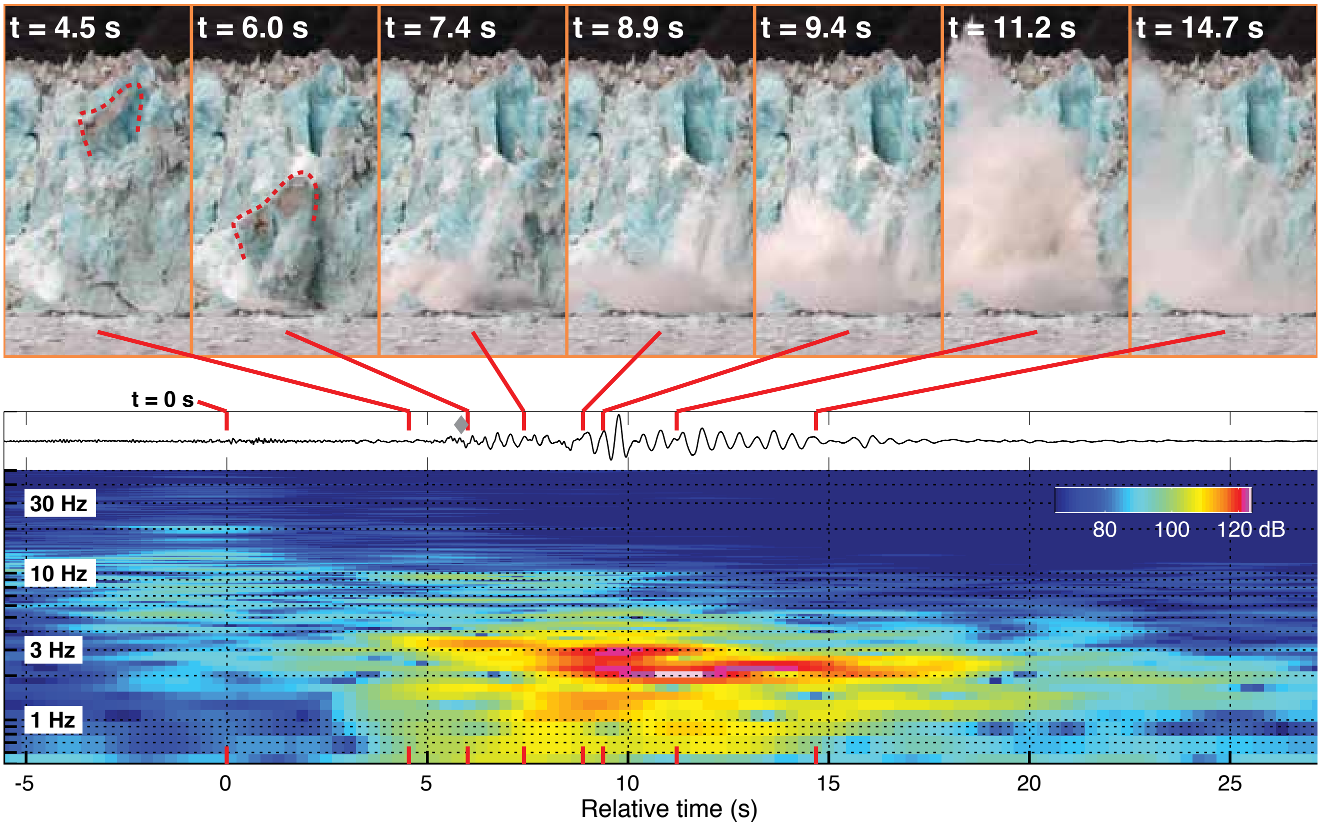

Figure 6: Video stills of calving event "Bloc" at the terminus of Yahtse Glacier, unfiltered seismic waveform and spectrogram of waveform. Terminal cliff is approximately 60 m tall. Event has an observer magnitude of 3 and a 18298 nm /s maximum ground velocity on the vertical channel of BOOM. In the first two panels from video, the top of the major detached block is outlined with red dashed line. Ice associated with the calving event is observed to begin falling at UTC 7 Sept 2010 22:13:50.3 (T=0). The time of each video panel is identified in seconds relative to t=0 and marked on the seismic data by vertical red ticks at the top of the waveform and bottom of the spectrogram. Seismic data has been shifted forward 0.95 s to correct for seismic wave travel time. The spectrogram presents the velocity of the sensor (in dB) as a function of frequencies between 0.5 and 50 Hz, as a function of time (From Bartholomaus et al, 2012).

The integration of GPS and seismic instrumentation also fosters novel multidisciplinary research. For instance, recent calving of giant tabular icebergs from the Ross and other ice shelves has spurred interest in the deployment of seismographs on large floating ice bodies to address fundamental questions associated with iceberg-iceberg and iceberg-sea-floor collisions (MacAyeal et al. 2008; Martin, Drucker et al. 2010) and with ice shelf stability and proposed disintegration mechanisms. Additional recent and novel research has centered on using floating seismometers, in consort with land-sited systems, as wave state sensors to assess wave effects on Earth's largest floating ice bodies and temporal trends in extreme wave events and their effects on tidewater glacial and coastal systems (MacAyeal, Okal et al. 2006; Okal and MacAyeal 2006; Aster, McNamara et al. 2008; Wiens, Anandakrishnan et al. 2008; Aster et al. 2010; Bromirski et al. 2010) and to identify wave events generated by regional calving (MacAyeal et al. 2009). In addition, seismographs have recently been shown to function usefully as strainmeters and ocean state sensors. Seismic noise from sub-ice water flow furthermore potentially offers unique information regarding the transport of water through or beneath glacial systems, which, for marine-based systems, is one of the most elusive processes involved with glacier instability.

Collocated on rock, GPS and seismic stations are also of great importance to advancing understanding of ice mass balance by providing critical constraints on models of post-glacial rebound (or glacial isostatic adjustment: GIA) (Fig 7). Understanding the GIA correction to GRACE and altimetry-based satellite mass loss estimates is essential for constraining ongoing ice mass loss.

Models of GIA are based on two types of inputs, namely an ice history (when, where and how much ice mass change occurred from the Last Glacial Maximum to present), and mechanical layer thicknesses and rheologies governing viscoelastic response of the solid earth. Substantial unknowns in both of these GIA model inputs results in marked differences in predictions of the distribution and amplitude of crustal motions due to GIA (e.g., Peltier, 2004; Simon et al., 2010; Whitehouse et al., 2012). The viscous response (which constrains mass change since the Last Glacial Maximum), the transitional viscoelastic responses that are sensitive to the last 100 to 1000 years of ice load, and the immediate elastic response to present-day ice load changes, can all be modeled and understood by incorporating data from continuous GPS measurements. Seismic images of earth structure are correspondingly needed for GIA studies to constrain mantle viscosity and the elastic thickness of the lithosphere.

2.2 Solid earth structure, tectonics and ice sheet stability

Polar continental regions represent important elements of the global plate tectonic circuit and contain cratonic cores that have been a part of this system since the Archean. Antarctica and Greenland also constitute climatologically key regions where Earth's major ice sheets

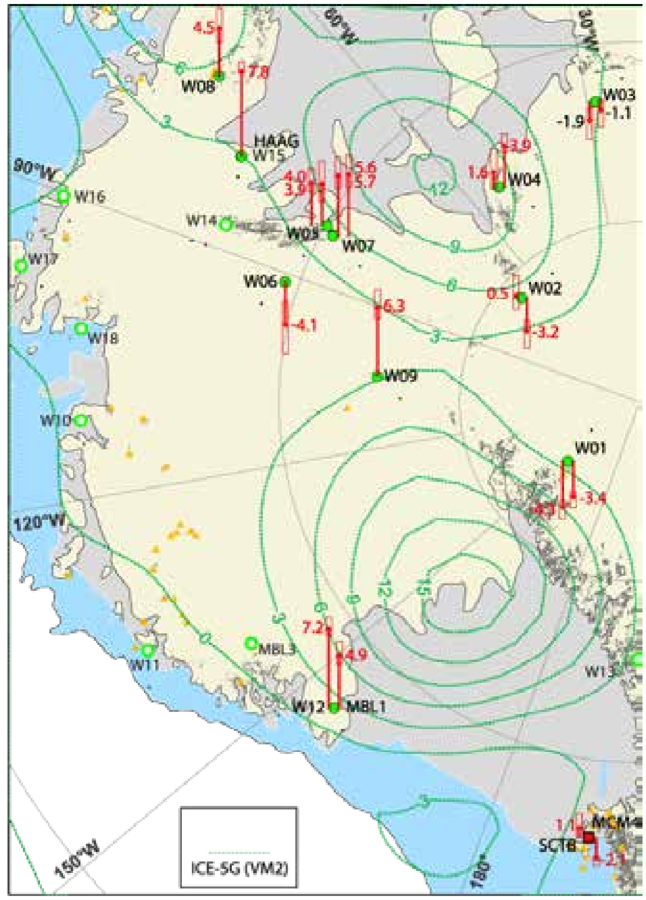

Fig. 7: Observed vertical velocity field from campaign GPS and autonomous GPS stations in West Antarctica compared with the predictions of ice sheet model ICE-5G (green contours in mm; Peltier 2004). Open green circles show sites where existing data are insufficient to constrain uplift. The misfit between the ice model predictions and observed uplift indicate the necessity of revising ice mass change estimates in association with improved mantle rheological models (modified from Bevis et al., 2009). Red arrows show velocities to scale and red rectangles indicate errors.

interact with both ongoing geodynamic processes and inherited tectonic features. These processes determine the topography, heat flow, and hydrology that control the evolution of polar glacial and meteorological systems through recent earth history. However, due to the size and thickness of the Antarctic and Greenland ice sheets, little is constrained about the geologic composition and tectonic history of Antarctica and Greenland, except via geological studies around the continental margins and along some mountain fronts where outcrops are exposed.

Modeling seismic and GPS observations collected at remote stations draws on a rich array of methods developed on other continents, and is one of the best ways to determine present structures and processes and to infer the past evolution of these key continental regions. For example, in Antarctica, polar ice sheets are thought to have first formed in the Gamburtsev Subglacial Mountains, near the center of the continent, yet the history and tectonic nature of this mountain range have been totally unknown. Observations carried out by a network of seismographs deployed during the International Polar Year (2007-2009)

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have recently revealed that the lithosphere beneath the mountains dates back to the Precambrian (> 550 Ma), and that the elevation of the mountain range is supported by a buoyant, thickened crust, as opposed to the mantle (Fig. 8). This shows that the mountains pre-date Cenozoic glaciation and have formed a key part of Antarctica's paleogeography for hundreds of millions of years.

In contrast to cratonic East Antarctica, West Antarctica has undergone widespread Mesozoic and Cenozoic tectonic activity, with recent and active volcanism found at several locations near Ross Island (Mt. Erebus) and in Marie Byrd Land. The Transantarctic Mountains (TAM) extend approximately 3500 km across the continent, and represent the only transcontinental mountain range in the world whose origin cannot be linked to plate collision. Active extension along the West Antarctic Rift System (WARS) began in the Mesozoic and may be continuing at a very slow rate today. Seismic tomography images, constructed with data obtained from seismic networks, reveal very slow upper mantle velocities beneath the WARS that suggest continued mantle-driven tectonism (Fig 9). Antarctica thus provides a number of excellent opportunities to advance our understanding of globally important geodynamic processes, such as craton formation, continental rifting and volcanism, plateau uplift, and mountain building. In addition, understanding the motion between tectonic blocks within West Antarctica could be important for explaining discrepancies in the global plate motion circuit.

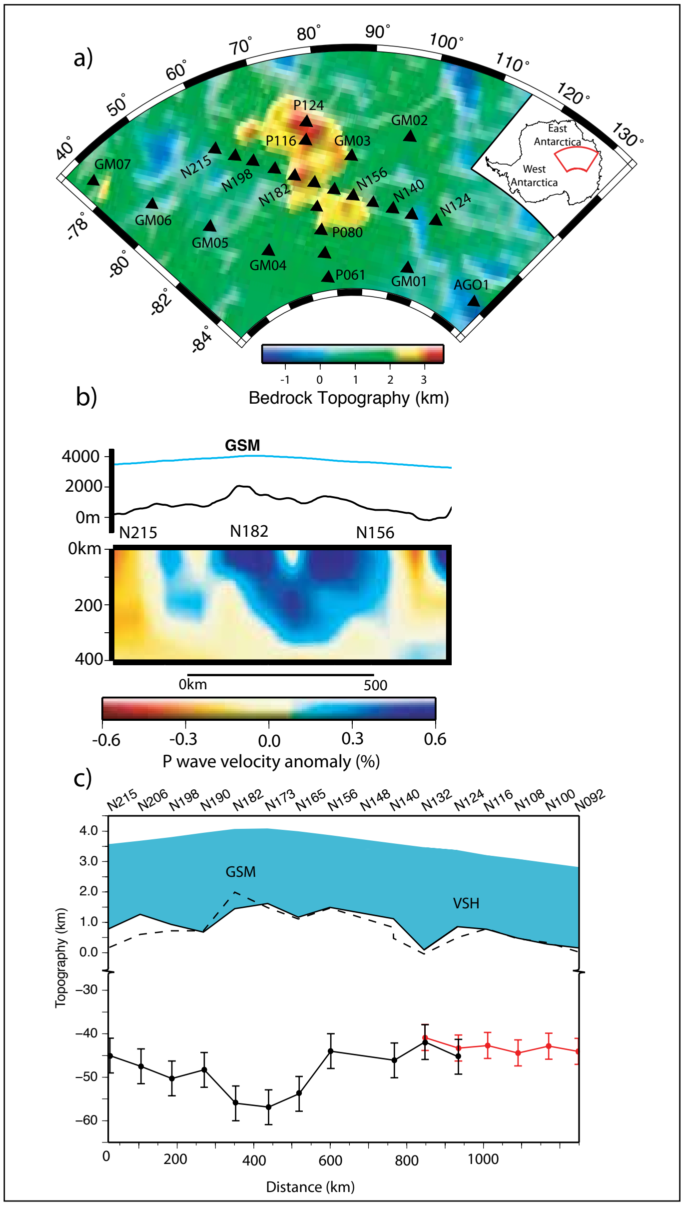

Figure 8: Results from AGAP/GAMSEIS showing seismically fast mantle structure and thickened crust under the Gamburtsev Subglacial Mountains (GSM). (a) BEDMAP elevations across the GSM and GAMSEIS station locations. (b) P wave tomography image from Lloyd et al. (2011). The blue line shows ice elevations, and the black line shows bedrock elevations. (c) Crustal thickness estimates from modeling S-receiver functions (Hansen et al., 2011) showing >10 km of crustal thickening under the GSM. The red line shows crustal thickness estimates from Hansen et al. (2009) using TAMSEIS data. VSH= Vostock Subglacial Highlands.

Key science questions include:

- What is the role of topography, heat flow, geology, and geomorphology in the initiation and dynamics of ice sheets?
- What are the thermal and rheological properties of the upper mantle and what are their influences on glacial isostatic adjustment?
- What are the origin and history of major mountain ranges?
- What is the history of tectonic extension, erosion, and volcanism in West Antarctica and its influence on ice sheet development?
- What is the role of the Iceland mantle plume in Greenland's tectonic and glaciological history?
- What is the geothermal heat flux beneath earth's ice sheets?
- How is sediment transported beneath and around the ice sheets?

Important questions of tectonic evolution and lithospheric development also remain unanswered in Greenland. Much of the continent was assembled in the Archean and early Proterozoic, with Himalayan-scale deformation occurring in the East Greenland Caledonides during the early to mid-Proterozoic. The inland extent

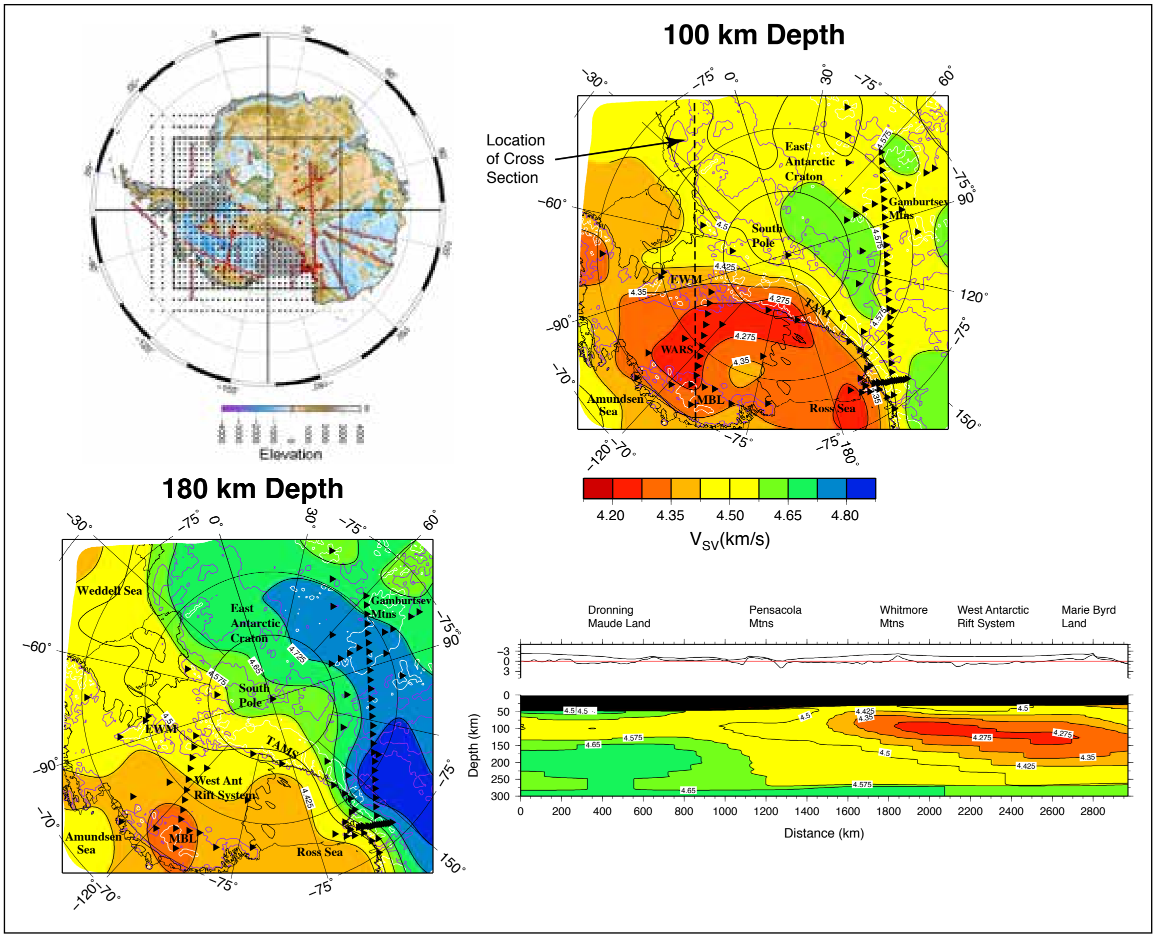

Figure 9: Mantle structure of West Antarctica and adjacent parts of East Antarctica from Rayleigh wave tomography using POLENET/ANET, AGAP, and TAMSEIS data [Heeszel, 2011]. The West Antarctic Rift System is characterized by slow velocities indicating high mantle temperatures, whereas East Antarctica shows fast velocities indicating thick cold continental lithosphere. Deeper slow velocities beneath the Marie Byrd Land dome may indicate the upper extent of a mantle plume.

of the Caledonide deformation is poorly known, as are probable contrasts in lithospheric strength and composition at sutures between cratonic blocks. The Iceland hotspot is believed to have initiated either under Greenland or under the present-day Alpha ridge in the Arctic Ocean, with Greenland then passing directly over the hotspot; either scenario is likely to have affected the nature of Greenland's lithosphere and associated heat flux. The nature of the hotspot interaction with Greenland is unknown, and can only be revealed through the ice sheet by geophysical means. The answers to these questions have important implications for tectonics, processes of craton formation, ice-sheet development, and the modern-day lithospheric response to ice-mass loss.

The relevance of solid earth structure and tectonics to ice sheet dynamics and sea-level rise is clear. Geodynamic and tectonic processes in Antarctica and Greenland have strongly influenced the history and evolution of polar glaciation and climate through first order effects on geothermal heat flux, lithospheric strength, mantle viscosity and tectonic geomorphology. Understanding geodynamic processes at high latitudes is important for determining present-day conditions and for predicting the future behavior of ice sheets. Isostatic rebound modeling requires good knowledge of lithospheric and asthenospheric thicknesses and mantle viscosity (e.g. Ivins and James, 2005). Coupled ice-sheet climate models (e.g. DeConto and Pollard, 2003) require estimates of sediment thickness at the base of the ice sheet, which can lubricate the ice-rock interface. In particular, high heat flow could produce sub-ice water that reduces bed friction, and may aid the formation of subglacial lakes. New and denser seismic and GPS data are critical for advancing our knowledge of solid earth structure and tectonics in polar regions and consequently vital to understanding ice sheet stability and sea level rise.

2.3 Deep Earth Structure and Processes

Seismic instrumentation in polar regions is also facilitating studies of the deep planetary interior that have previously been precluded by sparse station coverage at high latitudes. One example is inner core structure, for which polar recordings are crucial due to the approximate alignment of the fast axis of inner core seismic anisotropy with the Earth's spin axis (e.g., Sun and Song, 2002). As shown

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Mt Paterson, Antarctica: Joint IRIS/UNAVCO POLENET station in Antarctica.

in Fig. 10, PKIKP (or PKPdf) phases recorded in Antarctica often show large travel time anomalies due to inner core anisotropy. In this case the anomalously fast PKIKP arrival times can be fit by a structure in which 3% polar-aligned anisotropy occurs in the outermost inner core beneath southern Africa. Networks of seismographs in polar regions will allow these and other variations in deep earth structure to be mapped out and studied in much greater detail than is currently possible.

Key science questions include:

- What is the 3-D distribution and variability of seismic anisotropy in the inner core?
- What is the nature of the lower mantle and core-mantle boundary in the far southern hemisphere?
- Are there lower mantle anomalies that correlate spatially with plateau uplift, volcanism, and rifting in Antarctica, linking Antarctic tectonics to deep mantle dynamics?

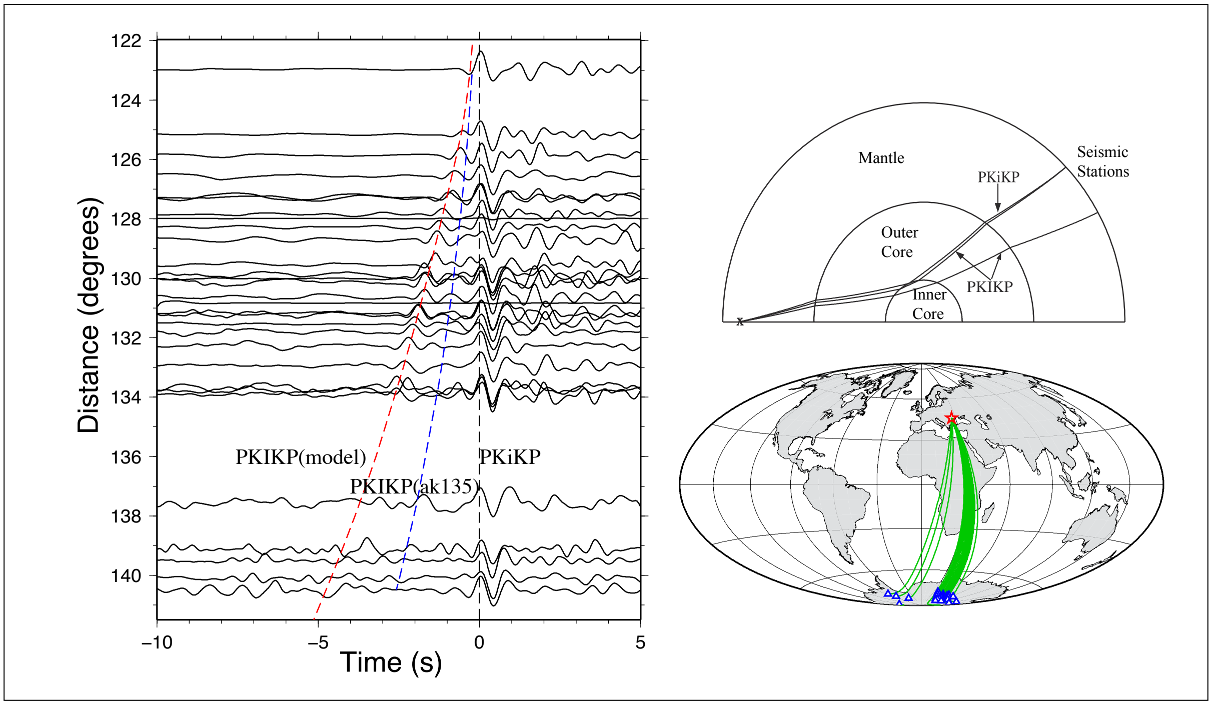

Fig. 10: PKP phases (from an earthquake on Apr. 25, 2009) sampling the top 100 km of the inner core beneath southeast Africa, recorded at POLENET and AGAP seismic stations. The waveforms are aligned with the inner core reflection PKiKP (black line). Blue line shows the prediction of inner core traversing PKIKP arrivals from the standard AK135 model. The actual arrival times of PKIKP (red line) are far ahead of predictions and can be fitted by a new model that has 3% anisotropy near the top of the inner core. (Right) Figures showing the PKP ray paths (from Sun et al., 2010).

3.0 UNAVCO POLAR SERVICES

In this chapter, the current capabilities and governance of UNAVCO Polar Services are described and examined in light of the projected growth in the need for facility support (see Chapter 1). Recommendations are made to address challenges arising from supporting past and current projects, in addition to challenges from increasing demands for facility support. These recommendations provide guidance on the support required to meet community needs for polar facility services, and on the management and governance of those services. An abbreviated compilation of the challenges and recommendations can be found in the executive summary.

3.1 Overview of UNAVCO Polar Services

UNAVCO has a long history of supporting polar projects with geodetic instrumentation and engineering services. The 1995/96 Antarctic field season was the first season that the NSF Office of Polar Programs directly funded UNAVCO to provide full scale high precision differential GPS support to the United States Antarctic Program. Funding was received via supplements to UNAVCO's grant hosted by UCAR in Boulder, Colorado. The projects supported included GPS surveying of sampling locations, augmentation for aircraft navigation, campaign measurement of ice streams and creation of topographic maps of ice and rock features. Resources deployed numbered some dozen GPS receivers and two UNAVCO field engineers to provide technical and logistical support, data processing services, and PI and student training. Although some early work was done in Greenland in 1987, PI project support began in earnest in Arctic regions in 2002.

With the establishment of UNAVCO as an independent, non-profit, university-governed consortium in 2002, OPP Arctic and Antarctic funding began to be included in UNAVCO's 2003-2007 core Cooperative Agreement. The polar support program grew in scope with the increasing number of funded PI projects, and the availability of a growing number of polar field-worthy campaign units in the UNAVCO pool. Science problems were also identified that required precise observations for longer periods of time. The next significant leap came with the International Polar Year (2007-2009). In conjunction with the UNAVCO/IRIS NSF MRI project "Collaborative Research: Development of a Power and Communication System for Remote Autonomous GPS and Seismic Stations in Antarctica" (hereafter referred to as the MRI power/comms project), technologies were developed that allowed for the first time year-round operation of GPS receivers for a range of new applications, including tectonics, measurement of the response of the crust to glacial isostatic adjustment, and time-varying ice dynamics. The IPY POLENET project (ANET and GNET and related projects) resulted in growth in the number of continuously operating GPS (cGPS) receivers from a few cGPS survey base stations in 2006 to the current 120 in Greenland and Antarctica. In addition, over 60 systems (cGPS and power) have been constructed by UNAVCO and deployed for longer-term installations by UNAVCO engineers or by Principal Investigators and their teams trained by UNAVCO staff. The growth in number and complexity of support is reflected in the fact that the number of UNAVCO pool GPS instruments in campaign and longer-term deployments has grown from 25 in 2002 to 325 in 2012.

An additional instrument was added to the geodetic toolbox with the acquisition of the OPP-funded Terrestrial Laser Scanning (TLS) System for Polar Research. This instrument, with GPS registered targets, gives the capacity to acquire millions of geo-located 3-dimensional points for determining ice and land surface topography and shape and their change over time. This technology has been embraced by the research community and has become a full-fledged part of UNAVCO PI support. As has been the practice, EAR shares resources with the OPP program, and the five EAR-funded TLS instruments are loaned for use with OPP projects when available.

The increase in scope of UNAVCO-supported OPP research has led to a steady increase in staffing. Currently UNAVCO has seven technical staff dedicated to OPP support providing project management, field engineering, development and testing, operations and maintenance of networks, data archiving and curation, and instrument support. Following a recent reorganization, the polar project staff now work in the newly formed Geodetic Infrastructure group, providing more synergism with other UNAVCO field programs and better ability to relieve staffing pressure through cross training.

3.2 Current Structure/Organization

Within the UNAVCO Facility, there is a specific group tasked with managing the large NSF-OPP pool of GPS, LiDAR and ancillary equipment, and supporting scientific studies in the Arctic and Antarctic. The Polar Services Group provides end-to-end support to funded investigators, and is led by a Project Manager, currently Joe Pettit. Most of the day-to-day tasks are shared among the group's staff members, except for equipment preparation/maintenance and field TLS support, both of which have a dedicated FTE (Full-Time Equivalent). Support tasks and their FTE

SUPPORT TASK	CURRENT ASSIGNED STAFF POSITIONS (FTE)
Project management	1.0
Technician Support (Equipment preparation, maintenance)	1.0
Engineering Support	
Network support	4.75 + .5
Continuous GPS projects	.75+.25*
Community base stations	.75
Campaign GPS projects	.25
TLS support	1.25
Development and testing	1.25
	.5+.25*
Data management (Downloading and archiving, metadata, software support)	0.25
TOTAL	7 + 0.5

Table 1: Tasking and FTE (Full-Time Equivalent) allocations for the UNAVCO Facility Polar Group. Asterisk denotes staff time contributed from outside the Polar group for field deployments as well as general development and testing support related to GNSS technology.

3.3 Summary of Key Services

The scope of UNAVCO Facility Polar Services can be divided into three major elements: continuous stations, campaign deployments, and equipment development and testing.

Continuous stations are defined here as those which remain deployed for at least one year, including:

- Networks: A network is a set of sites with an expected lifetime of more than 3 years, a science PI, and for which UNAVCO has primary O&M (operations and maintenance) responsibility. Both office and field support staff are involved in supporting these networks, which include approximately 120 stations within the ANET, LARISSA, Erebus, WISSARD, and GNET networks.
- Continuous GPS (cGPS) and power systems: This category includes continuous cGPS stations, which do not fit within the definition of a network, as well as power systems provided to Principal Investigators for non-GPS instruments. Such projects often require modest amounts of custom engineering or integration activity. The annual load is approximately nine projects per year, with an average of four systems per project. About 60 pool receivers are currently required to support this function.
- Community base stations: Support for community base station systems has been a successful and efficient service to local science communities at several polar research stations for over a decade. The following research sites currently have UNAVCO-supported systems: Antarctic sites at Palmer Station, McMurdo Station, South Pole Station, Lake Hoare, and WAIS Divide; Alaskan sites at Barrow (BASC), Atqasuk, and Toolik; Summit Station in Greenland.
- Data handling and archiving services: Successful execution of long-term base station projects requires a moderate level of attention to data flow and archiving tasks. Although polar personnel perform some of these functions, there is also leveraging of the existing UNAVCO data center infrastructure to support polar projects. While the data center has not historically been funded by OPP, it is a service UNAVCO provides for the benefit of polar Principal Investigators. Short-term deployments (below) also utilize the UNAVCO data center to a lesser degree.

Campaign deployments are defined here as those which occur over the course of one Arctic or Antarctic field season. These include:

- Campaign GPS projects. Traditional campaign projects involve short-term deployments of GPS receivers, surveying activities, data processing, and training for PI groups. These projects have remained steady at about 30 per year. However the average number of receivers per project has grown substantially, and over 140 pool receivers are now required to support this function.
- Ground based LiDAR, or Terrestrial Laser Scanning (TLS). Since the acquisition of the Optech ILRIS36D scanner, polar TLS applications have grown steadily; with a current average of 12 PI projects supported per year. This growth is attributed to several factors, including a raised level of community awareness for potential applications of TLS, availability of support from the UNAVCO Facility as a result of NSF investment, and scanning instrument improvements, which allow for better results at a faster pace. TLS proj-

ects tend to be time intensive due to the complexity of the instrument and the data post-processing. Future demand growth is estimated at a minimum of 2 projects per year for the foreseeable future.

Equipment development and testing is also provided by UNAVCO Polar Services, including:

- Ongoing incremental technology developments that are performed as part of UNAVCO's core services to the PI community. These developments are intended to accommodate modest improvements in systems design, and to respond to component obsolescence and other inevitable issues that require engineering attention.
- Major technology developments that are also within the capability of UNAVCO Polar, as in the successful completion of the remote stations MRI project with IRIS PASSCAL. For this type of development, dedicated funding and allocation of resources above and beyond our core level of support are required.

The current UNAVCO Facility Polar instrumentation pool is shown in Table 2, including the estimated baseline level recommended through the next Cooperative Agreement performance period of 5 years. The pool has grown to this level in response to project demand, as there have been more projects deploying larger numbers of instruments for longer durations in both the Arctic and Antarctic.

3.4 Facility Support

In this section, specific aspects of facility support provided by UNAVCO Polar Services are described. The section is divided between continuous stations, campaign deployments, and equipment development. For each area, the services provided are reviewed, the challenges in providing the level of support desired by the community are discussed, and recommendations are made to address those challenges.

Some recommendations, however, are more general and universal to UNAVCO polar support, and are presented first.

Recommendations

• It is critical to maintain a capable, well-trained support team to meet the existing and future demands of NSF-OPP funded projects. To provide adequate support now and into the future, while avoiding inefficient fragmentation of responsibilities, it is recommended that additional UNAVCO personnel be assigned to support polar projects. Increased staffing is central to maintaining the existing strengths within the group as well as meeting the challenges of future projects.

• Increase the level of cross training within and between Facilities, on three fronts.

1) Better distribute technical knowledge among members of the UNAVCO Polar Services group. Greater redundancy must be achieved by a targeted broadening of skill sets among the group so that critical knowledge does not reside with a single person.

2) Enhance cross training within the broader UNAVCO facility. In recent years this has improved the utilization of existing personnel, for example allowing UNAVCO Plate Boundary Observatory engineers to deploy to Antarctica. Such efforts should be continued.

3) Foster knowledge sharing between the UNAVCO and IRIS Facilities. The Facilities often work closely in the field, including logistics sharing, and there have been numerous instances where IRIS field engineers have contributed significantly to UNAVCO fieldwork, and vice versa. Improved cross training on equipment will ensure that field teams can optimize field operations, capitalizing on all such opportunities when they arise.

• Create enhanced training materials and make them available as a resource to the community. Training sessions at UNAVCO and in the field, along with written instruction manuals, have greatly enhanced the ability of PI field teams to successfully execute field instrumentation projects. However, a broadening and standardization of training materials, including online distribution, will further increase confidence and efficiency of field team operations.

• An improvement in long-term storage and staging space at field logistics hubs is needed, in particular at McMurdo Station. The amount of time spent reorganizing, repacking, and redistributing hardware

ITEM	CURRENT QTY	ESTIMATED QTY 5 YEARS	ATTRITION/ REPLACEMENT
Continuous Stations			
Network nodes	120	*	*
cGPS (standalone/	60	60	5/yr
Community Base Stations	10	15	1/yr
Campaign GPS Receivers	130	150	10/yr
LiDAR	0	2	n/a

Table 2: The UNAVCO Facility Polar Instrumentation pool enumerated by equipment type and function. Asterisk indicates that the requirements for network receiver acquisition and attrition/replacement are captured in science proposals.

Fig 11: UNAVCO engineer moves standalone continuous GPS station to the surface at Coulman High.

sometimes exceeds 25% of the field team effort. A larger amount of dedicated, long-term staging space for geophysical field projects is needed to improve efficiency of fieldwork and reduce wasted time.

3.5 Continuous stations

3.5.1 Services provided

UNAVCO Polar Services is tasked with a significant level of responsibility for approximately 180 continuous stations throughout Antarctica and the Arctic, including networks, continuous GPS and power systems, and community base stations. Responsibilities involve planning and budgeting, purchasing, construction, configuration and testing, assistance with logistics planning, shipping and staging, field deployments, data flow monitoring, metadata management, data archiving, documentation, and training of PI science groups. Providing these services for continuous stations is now one of the core competencies of the Polar Services group at the UNAVCO Facility.

For remote autonomous GPS stations, the central design originated from the MRI power/comms project. The resulting stations combine solar, wind, and battery power with Iridium satellite communications to create a system of proven reliability that meets the challenges of continuous data collection in extreme environments.

Notable achievements of the services provided include the following:

1) Year-round operation of remote GPS stations is now commonplace. For stations equipped with communications, mean time between failures (MTBF) now exceeds 2 years, and overall data return has averaged 88% from 2006 to present.

2) Strong coupling exists between PI science objectives and the hardware products delivered. Systems are provided which are appropriate to the requirements of the scientific instrumentation (power consumption, remote communications, necessity of uninterrupted year-round data recording), logistical constraints (size, weight, method of deployment), and environmental conditions (snow/ice or rock surface, duration of winter darkness, minimum temperatures, maximum wind speeds).

3) Modularity and scalability are features of the system designs. A variety of power generation and power storage components, enclosures, and mechanical assemblies are available. This allows construction of systems of diverse size, weight, power, and operational requirements without a complete redesign.

4) Remote communications enable better and more rapid scientific results, and assist greatly with planning of field operations logistics. At stations equipped with communications, approximately 75% of available data has been retrieved remotely.

5) Since reliable power and communication platforms for remote instrumentation are now available as a service from the Facilities, opportunities for enhanced projects and better efficiencies are offered to science Principal Investigators, especially those new to remote polar instrumentation projects.

6) These instrumentation platforms are adaptable to instruments other than GPS receivers. At present, UNAVCO has supplied power systems for ~10 such stations, including weather and camera systems, ozone sensors, and ocean temperature instruments.

3.5.2 Challenges

A number of significant challenges have been identified to providing improved services for continuous stations.

1) Fulfilling commitments to PI projects with delivery of high quality, fully tested instrumentation systems while simultaneously pursuing technological developments and propagating them to existing stations is difficult with the existing staffing.

2) A similar challenge arises from simultaneously maintaining large networks and infrastructure in a systematic, structured fashion while remaining agile and responsive enough to support smaller and newer cutting-edge PI projects.

3) Lengthy field seasons in demanding conditions put a great deal of strain on the UNAVCO engineers each year. UNAVCO has made headway in limiting the length of field deployments, training other engineers internally, and training members of the PI field teams, but there is still a heavy burden put on the primary UNAVCO polar engineering team. Expanding technical capability beyond a critical few requires that cross-training is examined in every practical way, in particular among members of the UNAVCO polar group but also between members of GPS and seismic field teams.

Recommendations

- Support the UNAVCO Facility to maintain a limited stock of strategic long-lead time items. This greatly reduces preparation time and enhances the Facility's ability to rapidly respond to projects, which are approved and/or funded a short time before deployment is required.
- Extending project award cycles for field deployments to four or five years from the current typical three years would ensure adequate preparation before equipment is deployed to the field, increasing the chances for success.
- UNAVCO should continue to maintain a state of the art pool of equipment suitable for polar applications to address equipment obsolescence and attrition, technology advancements, and specialized polar science requirements.

3.6 Campaign deployments

3.6.1 Services provided

UNAVCO Polar Services provides a steadily growing level of campaign GPS and TLS support to PI projects. Here, the term "campaign" refers to deployment of equipment during a single Antarctic or Arctic field season. Such projects may require field GPS surveying, portable differential GPS systems, arrays of autonomous GPS systems designed to operate unattended all summer, and TLS scanning and geo-referencing of land and ice features.

Support to campaign projects can be extensive, including engineering design, training, field planning assistance, equipment preparation, system fabrication and shipping, equipment testing and staging, direct field support, and data processing/archiving. In many cases the engineering team will work with a project from initial proposal support through final data archiving. During an Antarctic field season, up to five UNAVCO engineers may deploy on an overlapping schedule to better enable efficient support for campaign projects.

Campaign GPS projects are steady at about 30 per year, however the average number of receivers deployed per project has grown substantially. Currently about 140 pool receivers are required to support this function. Various equipment types are in use, including Trimble R7/5700 series, Trimble NetRS and Trimble NetR9 receivers.

In 2007 UNAVCO added Terrestrial Laser Scanning (TLS) to its capabilities with the purchase of one Optech laser scanner. This NSF-OPP owned LiDAR was purchased with MRI funding as a pilot project, and demand for LiDAR data acquisition has since expanded TLS into a core service provided to NSF-OPP investigators. Campaign TLS projects currently number an average of twelve per year, with steady growth in demand expected in the coming years.

The OPP-owned Optech unit has reached obsolescence, however four additional TLS scanners have been purchased by UNAVCO EAR, with a fifth unit shared with a member institution. These resources are currently shared with the Polar group, however scheduling conflicts are beginning to materialize as the popularity of this service expands. UNAVCO Polar will propose to acquire two modern ground based LiDAR units to continue the current level of support while meeting potential growth in demand. Two instruments are required to provide a backup capability in the event of instrument failure in the field to minimize risk to projects.

Notable achievements of the services provided include the following:

1) The UNAVCO campaign GPS equipment pool is rugged and versatile. Many aspects of these systems were recently redesigned, and at present the enclosures, receivers, antennas, and solar power systems (where needed) are more reliable than ever.

2) UNAVCO Polar Services provides and maintains GPS post-processing software for internal use as well as external use by science groups. Also, on a limited basis UNAVCO Polar Services can deliver complete processed GPS data sets to PI groups.

3) The TLS instruments have been proven to operate in polar environments. The TLS data sets, geo-referenced using ancillary GPS equipment, provide a powerful new capability for polar researchers.

3.6.2 Challenges

A number of significant challenges have been identified to providing improved services for campaign deployments.

1) To adequately support NSF-OPP projects, campaign equipment must be moved between the Arctic and the Antarctic in field seasons that are overlapping to a greater and greater degree. These projects have grown in size and complexity over recent years and require more time up front and in the field to properly execute. A significant

challenge for the campaign GPS pool is maintaining sufficient inventory to support Arctic and Antarctic projects while minimizing the need to constantly ship receivers and equipment between polar regions.

2) Individual projects have different requirements for power and enclosures, e.g., depending on deployment method, duration of the deployments, whether or not the equipment will operate attended or unattended, and the environment in which they are being used (snow/ice or rock). An ongoing challenge is to maintain an adequate and flexible inventory of components to execute a wide range of campaign projects, while ensuring the power systems and enclosures are compatible with the different receiver models in the pool. UNAVCO has partially met this challenge by engineering off the shelf solutions that fit the majority of project requirements. That said, there are still many unique project requirements that require significant engineering time.

3) Maintaining solid technical competence in GPS survey methods and data processing techniques is essential.

4) Trimble R7 and 5700 receivers are still heavily used in campaign GPS work, especially for kinematic survey tasks. However these receivers are no longer manufactured and the pool of these receivers is increasingly showing their age. On many occasions, use of newer receivers such as the Trimble NetR9 is impossible or not practical; therefore a new pool of receivers suitable for kinematic work is needed.

Recommendations

- Acquire two state-of-the-art terrestrial scanning instruments with the capabilities to meet science requirements identified by polar investigators, in order to satisfy the current demand and decrease dependency on NSF-EAR owned equipment.
- Improve the infrastructure associated with TLS operations to achieve parity with the GPS services that UNAVCO provides. This includes providing dedicated equipment, archiving, and ancillary services to polar PIs. If other emerging technologies are undertaken by UNAVCO, for example radar, it is recommended that a similar level of full and complete support be provided.
- Continue to refresh knowledge of GPS operations and surveying methods, and data post-processing among UNAVCO Polar Services personnel. Enhancing the training materials available to PI science groups is also recommended, as described above.
- As campaign GPS projects increase in scale, and as Antarctic and Arctic science field seasons lengthen and increasingly overlap, an ideal model would be maintaining separate pools of equipment for Antarctic and Arctic use. Although funding levels may not allow this, an intermediate solution would be to acquire enough systems such that repairs and updates are allowed during austral and boreal winter seasons instead of immediately returning systems to the field.

3.7 Equipment development

3.7.1 Services provided

In collaboration with IRIS and a team of experienced PIs, UNAVCO successfully completed the MRI power/comms project aimed at improving power and communications for continuous GPS stations, with all design goals achieved. Results of this project have greatly facilitated a wide array of PI projects, which required year-round continuous GPS data, including the large IPY POLENET initiative.

Since completion of this project, technical development has continued on an incremental level as part of the core services provided by UNAVCO. Examples of technical products delivered include wind turbines and charge control systems capable of operating in polar regions, advanced Iridium communications systems (in partnership with Xeos Technologies), a variety of mechanical systems optimized for use in diverse polar environments, formal handling of system metadata, and integration of selected non-GPS instruments. The power and communication systems are well documented, including instruction manuals and an online repository of technical information, available at www.unavco.org/polartechnology.

A second NSF-OPP MRI project was completed in 2007, in which a TLS scanner was acquired to ascertain suitability for use in the polar regions. During the course of this project, numerous technical issues were resolved and successful demonstrations with this instrument were achieved with several polar deployments. Since that time TLS scanning has become part of the core services of the polar group.

ANET cGPS station “BENN” in West Antarctica - *Courtesy Jeremy Miner.*

In collaboration with funded science groups, a "sensor web" concept was successfully developed and demonstrated in recent years. A small network of low-cost, rapidly deployed, solar-powered GPS units was deployed on a Greenland glacier, in an area presenting high risk of equipment loss. Data was telemetered using a point-to-point radio network to receiving stations on nearby bedrock, where it was downloaded using Iridium to the UNAVCO facility. This innovative technology holds promise for researchers seeking acquisition of data sets from similar "high risk" areas.

Advances in Iridium communications, through investments and collaboration with Xeos Technologies, have been made during the initial MRI project and subsequent incremental efforts. These devices have demonstrated significant advantages over off-the-shelf Iridium communications hardware, and are now being fielded with increasing frequency as replacements for historically failure-prone communications equipment.

UNAVCO has also redesigned much of the Campaign GPS equipment pool, resulting in improved performance and usability.

In addition, UNAVCO Polar Services maintains a high profile among the community of polar technology developers. Technical consultation with researchers and developers is a relatively common occurrence, with valuable information exchange in both directions. Members of the polar group have also been active participants in the Polar Technology Conference, serving on the steering committee as well as hosting the conference.

Notable achievements of the services provided include the following:

1) A collaborative spirit exists within UNAVCO Polar Services, resulting in significant technical advances. For example, past and present work with IRIS has increased the ability of PI projects to acquire more extensive and rich geophysical data sets. Also, a prototype project with the Automatic Weather Station group has demonstrated the ability to integrate a true polar-capable weather station with a standard UNAVCO polar GPS station. Finally, a joint project with Lamont-Doherty Earth Observatory and other PI collaborators produced a successful "sensor network" of quick-deploy GPS systems for hazardous on-glacier locations, with a data telemetry link to UNAVCO.

2) Systematic and rigorous testing procedures for equipment prior to deployment has improved data return.

3) Sustained support from professional engineering staff has allowed long-term development of polar technologies, resulting in mature, reliable instrumentation systems available to polar researchers worldwide.

4) Advances in communications to remote instrument stations has enabled more rapid and relevant generation of scientific results, and increased efficiency of field logistics. Where stations are equipped with communication systems, an average of 75% of available data has been retrieved remotely since 2006. Ongoing testing of advanced Xeos Iridium devices is yielding improvements in data return and reliability.

GNET cGPS Station "ASKY" in North West Greenland -*Courtesy Jeremy Miner.*

3.7.2 Challenges

A number of significant challenges have been identified to providing improved services in the area of equipment development.

1) The batteries at long-duration continuous stations will soon reach the end of their useful lifetime, however replacement of batteries is a logistically intensive undertaking – for example the POLENET stations have 12-24 lead-acid batteries per site. Actual serviceable life of the batteries will likely exceed the initial five year estimate, but a strategy and timeline for replacement must be made soon.

2) Obsolescence of the GPS receiver pool is a major issue. The Trimble NetRS receiver, which makes up 100% of the remote ANET, GNET, and LARISSA network sites, is aging, out of production, and will only become less reliable over time. Although the existing pool of NetRS units can sustain these networks for two to three more years, a suitable replacement receiver has not been identified. Identifying, testing, or custom engineering a receiver will be a sizable effort requiring staff time beyond that available from PIs or currently proposed for UNAVCO. Such a development and testing effort is not within the scope of the incremental, sustaining engineering activities that UNAVCO currently provides.

The Trimble 5700 and R7 receivers, which are heavily used for campaign deployments, are starting to show their age and attrition is increasing. For these receivers selection of a replacement model is straightforward; funding is the limiting factor.

Recommendations

• Establish a strategic, sensible plan for replacement of batteries at long-term continuous stations. This strategy must include objective analysis of battery health and realistic predictions of usable lifetime, as well as an assessment of emerging battery technologies to determine if increased power density and decreased mass, albeit at higher cost, will offer substantial logistical efficiencies. Key PI stakeholders must also be involved in this process, as the science implications and logistics costs of this operation are substantial.

- Improve designs for continuous stations to eliminate single-point failures and increase reliability. Several instances of system failures have been observed due to one key failure, for example cable damage from wildlife. Since the average interval between site visits is greater than one year, loss of data due to such causes must be minimized.
- Continue focused development on Xeos Iridium-based communications solutions for polar use. Increased reliability of remote data retrieval will continue to benefit logistics planning and reduce the frequency of field site visits.
- A plan should be developed immediately to identify the next GPS receiver for continuous use in polar regions. Resources will be needed to implement a receiver replacement. This critical issue needs to be addressed by UNAVCO with close coordination from the community, perhaps as a MRI or equivalent project. An initial step forward might be a small workshop of key investigators.
- As attrition of campaign GPS receivers increases, failed devices should be replaced with modern units.
- Continue close collaboration with the IRIS polar group to evolve power and communications for continuous stations. Although collaboration between Facilities is ongoing at an incremental level, it is thought that technological advances may now present another opportunity for large advancements in remote station design, similar to the first joint MRI which resulted in a quantum leap forward in continuous GPS and seismic station performance. An assessment of available technologies should be performed, and a follow-on MRI proposal developed if warranted.
- Collaborations with other members of the polar instrumentation community should be cultivated, for example the Automatic Weather Station group or the space physics community, to maximize the science return on the investment in remote autonomous stations.
- The "sensor web" concept, successfully demonstrated at a prototype level, should be brought to maturity with a second round of engineering development. However the scientific community must demonstrate sufficient demand for this technology and initiate further development.

3.8 Governance

Within the UNAVCO governance structure, the joint IRIS-UNAVCO Polar Networks Science Committee (PNSC; see Chapter 5) is a committee of the UNAVCO Board that is unique in being shared with IRIS. The current UNAVCO governance structure including the PNSC, ensures that the UNAVCO community's needs are being considered in developing plans for maintaining polar networks in the larger context of all UNAVCO-supported polar science, and the overall UNAVCO mission.

The PNSC reports directly to the UNAVCO Board of Directors, while reporting its recommendations as well to the Geodetic Infrastructure Advisory Committee (GIAC). The PNSC chair or Vice-Chair (depending on who is the UNAVCO appointed member) liaises with the GIAC to ensure close coordination. In addition, the Terrestrial LiDAR Scanner Working Group and the PNSC maintain close communication to ensure that the needs of the polar TLS community are being served. The current crosscutting nature of the committee structure is working well to integrate the polar community within the UNAVCO governance structure and we recommend continuing this arrangement. We also recommend formalizing a communication plan to maintain effective contact between committees. A specific recommendation is to have the PNSC report to the TLS and GIAC committees at least annually at their meetings, either in person or by teleconference. The PNSC chair or vice chair will report status and recommendations of these UNAVCO committees relevant to polar support back to the PNSC.

Recommendations

- Continue the effective governance provided by the current cross-cutting nature of UNAVCO's committee structure
- Formalize a communication plan to maintain effective contact between committees, and have the PNSC report to the TLS and GIAC committees at least annually at their meetings.

POLENET cGPS Receiver and electronics - *Courtesy Seth White.*

4.0 IRIS POLAR SERVICES

This chapter parallels the previous chapter but with a focus on IRIS Polar Services. The current capabilities and governance of IRIS Polar Services are described and examined in light of the projected growth in the need for facility support (see Chapter 1). Recommendations are made to address challenges arising from supporting past and current projects, in addition to challenges from increasing demands for facility support. The recommendations provide guidance on the support required to meet community needs for polar facility services, and on the management and governance of those services. An abbreviated compilation of the recommendations can be found in the executive summary.

4.1 History of IRIS Polar Services

IRIS has a long history of supporting seismological studies in polar regions, with instrumentation and operational support for permanent and temporary stations provided by the Global Seismographic Network (GSN) and the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL), and data archiving, curation (including data and metadata quality assessment and control), and redistribution by IRIS Data Services and the Data Management Center (DMC). Deployments of PASSCAL equipment have been taking place since 1989, and GSN stations have been operational since the late 1980's. Decades of design, testing, field experiments, technological growth, and investment in instrumentation and services has enabled IRIS to facilitate the collection of state-of-the-art broadband seismic data in the extreme environments of the polar regions, areas of the globe that remain grossly under-sampled. The polar services provided by IRIS have leveraged, and continue to leverage, core capabilities enabled by NSF EAR funding to IRIS.

GSN: The GSN, a joint IRIS-USGS network of 153 stations, includes 5 stations in Antarctica and ~12 stations in the Arctic (Fig 12). The GSN station QSPA is the longest-running continuous observational instrument operating at the Amundsen-Scott South Pole station with continuous records from the 1957-58 International Geophysical Year through the present. Until the mid-1990s, all polar GSN stations were located at established facilities so that minimal work was required to cold-harden the station components. However, along with the infrastructure required to keep instrumentation within operational specifications comes associated noise from generators, heat fluctuations, personnel and building noise. Therefore, in the mid-1990s, IRIS and the USGS embarked on an effort to move the South Pole seismic station away from the base of operations, and, in 2002, the South Pole Remote Earth Science and Seismological Observatory (SPRESSO) was established, resulting in one of the quietest GSN stations in the world, particularly in the high-frequency band.

PASSCAL: PASSCAL support to PI-led projects has evolved from only providing standard equipment configured for non-polar experiments to providing specialized polar-rated equipment with support from a polar-trained staff. This evolution in polar-facility support has improved data quality and availability from partial, summer-only data collection to full, year-round operations with 24/7/365 command and control of station operations in some of the most remote polar regions.

Until around 2004, only 3 to 4 polar PASSCAL experiments per year were supported, and there was a lack of a unified approach to the polar station design between each experiment, as well as no formal way for the PIs to share design successes and failures. In 2004, IRIS began enhancing its capabilities to provide more robust operations in polar regions, procuring a cold-testing chamber to allow ambient temperature testing and evaluation of instrumentation. At about the same time, snow streamers (active source, tow-behind data cables and sensors) were procured for use by the active source community. As described in the previous chapter, in 2007, IRIS and UNAVCO received NSF MRI funding (MRI power/comms project) to develop the next generation of power and communication systems. As a result, UNAVCO and IRIS, with guidance from the Polar Networks Science Committee, have developed best practices, designs and new instrumentation that address operational conditions in a variety of harsh polar environments (e.g., extreme cold, high altitude, high wind). In 2008, IRIS received a second NSF MRI award to procure cold-rated instrumentation, allowing for the development of a modest pool of polar instruments and infrastructure.

Funding to IRIS for PASSCAL polar activities initially came from the NSF-EAR facilities program. It was recognized early on, however, that polar experiments required an incremental cost above the typical non-polar PASSCAL experiment. Consequently, beginning with the 2007 MRI award, PASSCAL began to retain a permanent and specialized staff to address and support the instrumentation and field needs associated with polar work. Since then, IRIS has received additional incremental funding from OPP/AES to continue supporting the polar PASSCAL staff.

4.2 Current structure/organization

Polar activities at IRIS fall under the Instrumentation

POSITION	Total PASSCAL FTE	OPP Or GLISN Funded FTE	PASSCAL Core Staff Leveraged by Polar	Total Polar level of effort (FTE)
Management	1.2	0.0	0.1	0.2
Admin	2.6	0.0	0.2	0.5
Data	3.1	0.7	0.2	1.3
Hardware	7.8	5.2	0.6	6.8
Logistics	3.0	0.0	0.2	0.6
Sensor	3.8	0.0	0.3	0.8
Software/Sysadmin	6.0	0.0	0.5	1.2
Total	26.3	5.9	2.1	8.0

Table 3: PASSCAL Staff

Services (IS) Directorate with high-level management provided by the Director of IS. Under IS, Polar management activities across IS are shared between the GSN and PASSCAL Program Managers with the GSN manager coordinating the overall IS polar activities and performing strategic planning for the polar programs while the PASSCAL manager leads the portable experiments conducted in polar regions. Day-to-day portable operations for PASSCAL are performed under a sub-award to New Mexico Tech through the PASSCAL instrument Center's (PIC) Polar Support Services and are supervised and coordinated by the PIC Director and principal investigator. For the GSN, there are no polar-specific staff at either IRIS, USGS, or IDA as polar work is undertaken as a part of normal GSN operations supported by NSF EAR.

IRIS PASSCAL polar activities are managed by the PASSCAL Manager and supported primarily by PIC staff hired specifically for polar work. Additional support is provided by the core PASSCAL staff (Table 3). The current staffing configuration reflects the history of IRIS Polar Services, where initially all staffing positions were supported by the EAR core budget. In addition to polar staff supported by OPP, IRIS received an MRI award (award period 2009-2013) to install the GLISN network in Greenland that includes ~1.6 FTE to support field operations and data recovery. Table 3 shows the polar-specific staff as well as the estimate of the PASSCAL core staff that are utilized for polar projects (estimated on the basis that ~20% of all PASSCAL experiments currently occur in polar regions). To date, there is no FTE support from NSF/OPP Arctic Sciences in support of polar operations, although nearly half of the experiments supported by polar services occur in the Arctic.

4.3 Summary of key services

a. GSN stations. 17 permanent polar seismic observatories are operated and maintained, providing open, real-time data to the community (Fig 12).

b. Longer-term networks. IRIS has been directly involved with the installation, operation, and maintenance of longer-term seismic stations in Greenland (GLISN project) and Antarctica (ANET/POLENET project) in response to community science initiatives.

c. Temporary networks. For both active-source and passive-source experiments, equipment, field support, and data management are provided by the PASSCAL program.

d. Equipment development. PASSCAL staff continuously work on improving polar instrumentation through testing and engineering development activities.

e. Data management. All polar seismic data are processed through the GSN or PASSCAL data/network-operations centers and are archived and distributed through the DMC.

f. International partnerships. All IRIS programs work to maintain and support international partnerships through collaborative experiments and technical interchange.

4.4 Facility Support

In this section, specific aspects of facility support provided by IRIS Polar Services are described. The

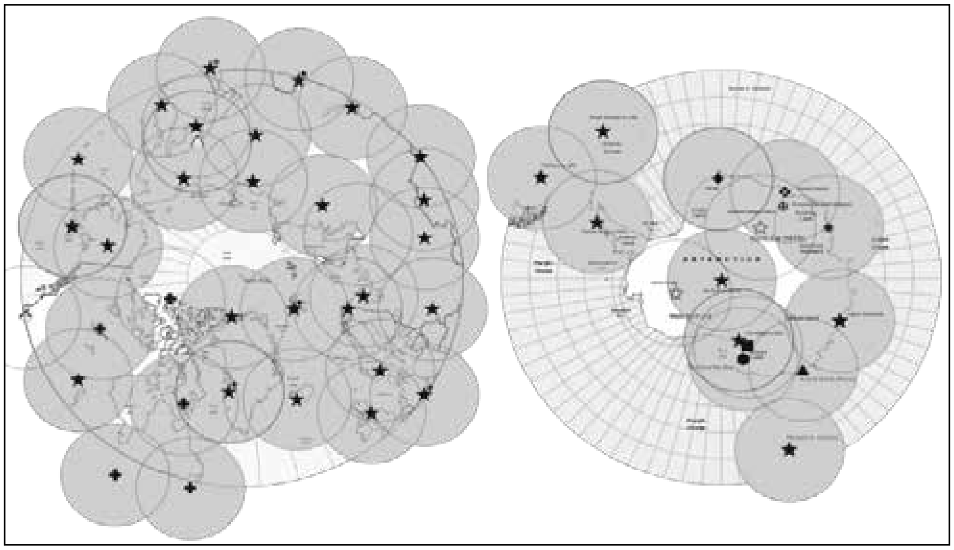

Fig: 12: Permanent Seismic Stations on a polar projection. Most are IRIS GSN stations with some additions from the FDSN contributors. Shaded circles show region within 5 degrees of a station.

section is divided between the GSN, longer-term networks, temporary deployments and equipment development. For each area, the services provided are reviewed, the challenges in providing the level of support desired by the community are discussed, and recommendations are made to address those challenges.

4.5 GSN stations

4.5.1 Services Provided

GSN stations in the high latitudes provide important coverage for global seismology. The long time series data from these stations provide critical information for understanding seismicity of the high latitudes, glacial seismology, and the large-scale structure of Earth's crust, mantle, and core. The stations also serve as a reference network for higher density, shorter-term seismic experiments in polar regions.

Five permanent GSN stations are operated in Antarctica, located at South Pole, Palmer, Scott Base, Lake Vanda, and Casey (QSPA, PMSA, SBA, VNDA, and CASY). All of these stations but VNDA are operated through the GSN partnership with the USGS Albuquerque Seismological Laboratory (ASL), with instrumentation support from IRIS. VNDA receives its operational support from the Air Force Technical Application Center in Florida, but was originally designed and installed by ASL staff as part of the Global Telemetered Seismograph Network (GTSN). Personnel for fieldwork at CASY is provided by the ASL and funded through the IRIS/USGS-GSN. Logistics support for two of the permanent GSN Antarctic stations (QSPA and PMSA) is provided by NSF/OPP through a continuing grant to IRIS and covers operational support, as well as travel to these locations for maintenance and upgrades. Logistics support for the Scott Base seismic station (SBA) is provided by the New Zealand Antarctic Program (station operations and infrastructure), although travel to the site utilizes USAP support. Logistics support for the CASY station (located at Casey Base) is supported by the Australian Antarctic program, although there are occasional logistics sharing opportunities with USAP.

The GSN also operates approximately a dozen Arctic stations in Canada, Greenland, Norway, Iceland, Finland, Russia, and Alaska. The Arctic GSN stations are located at larger facilities provided by international hosts with supplemental support from IRIS and the USGS. None of the GSN Arctic station operations currently utilize direct logistics support from NSF OPP.

Notable achievements of the services provided include the following:

1) Improvements in instrumentation and recording technology have expanded the capabilities and reach of permanent seismic facilities in the cold. Power requirements for recording systems have been reduced from kilowatt levels to 10s of watts and less. GSN and PASSCAL staff, supported by NSF and the USGS, have worked with equipment manufacturers to develop and provide low-power, cold-rated sensors and acquisition systems as off-the-shelf items. This has greatly reduced the cost and power budgets for permanent and temporary stations, and enabled the operation of permanent, remote autonomous facilities away from the "cultural" noise sources associated with major bases of operations.

2) The interpretation of seismic data, particularly in the context of interactions between the solid Earth and the cryosphere, atmosphere, and oceans, is aided by the availability of auxiliary geophysical data streams recorded at or near seismic stations. The deployment of remote, long-term, seismological observatories provides an opportunity to record such auxiliary data at a relatively small incremental cost in effort, equipment, and logistics. The concept has been proven at GSN stations, where co-located instrumentation at many stations allows the collection of geodetic, magnetic, and meteorological data. These data have great value to other science communities as well.

4.5.2 Challenges

A number of significant challenges have been identified to providing improved operation of the polar GSN stations.

1) Supporting the long-term, continuous acquisition of seismic data from polar regions continues to be a major challenge. Interruptions in continuous records adversely affect their scientific value, and many signals of interest are of low amplitude, requiring longer time series for their detection and evaluation. A challenge for enabling such observations is the need for stable funding support over decadal timescales coupled with finding ways to reduce costs by improving the efficiency of station operation.

2) There are several technical challenges facing the operation of all stations in polar regions, whether they are GSN, longer-term or temporary. Improvements in telemetry capacity are key to reducing the need for station visits: if all data can be returned via telemetry, station visits need occur only infrequently to repair problems or replace critical hardware. Currently, the ability to telemeter all recorded data from remote sites is limited by the high power consumption of telemetry technology. Reductions in the power required for full-bandwidth telemetry, and/or improvements in the power systems at remotes stations, would allow significant overall cost savings by reducing the need for site visits, and hence reducing logistics costs. Remote sites also require sufficiently robust enclosure and environmental control systems to allow sensors, data loggers, and communications equipment to operate efficiently under local environmental conditions for long periods of time (i.e., many years to a decade).

Recommendations

- Continue coordination with NSF/OPP on operations of existing Antarctic GSN stations
- Continue work on communications systems to allow retrieval of full bandwidth data from remote, autonomous stations
- Improve and enhance station capabilities through addition of related geophysical instrumentation

4.6 Longer-term networks

IRIS Polar Services has been involved with the installation, operation and maintenance of two community networks designed to provide continuous data over many years, the Greenland Ice Sheet Monitoring Network (GLISN) and the Antarctica component (ANET) of the Polar Earth Observing Network (POLENET) (Figs 13, 14). Support for GLISN has been provided primarily though the GSN program and for ANET through the PASSCAL program.

4.6.1 Services Provided

Together with international partners from nine countries in Europe, Asia, and North America, IRIS operates the Greenland Ice Sheet Monitoring Network (GLISN) (Fig 13). The network is designed to provide enhanced regional seismic coverage compared with the sparse global network of permanent seismic stations; enhanced geodetic coverage is also provided at sites on the ice sheet. An important aspect of the network is its ability to sense seismic signals generated in response to changes in the Greenland Ice Sheet and its outlet glaciers, whether those signals originate in the ice itself or in bedrock. GLISN stations record both high-frequency signals from earthquake sources in bedrock and low-frequency signals arising directly from ice motion.

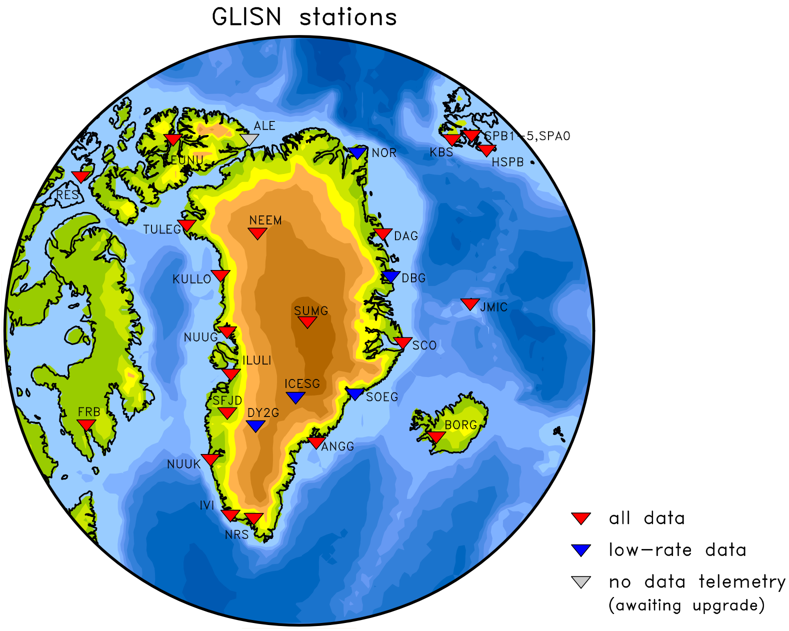

Fig: 13: Map showing GLISN stations.

Because of the need to assess temporal variability in the natural system, this is a longer-term observing network. The network also provides a backbone structure for temporary arrays operated in Greenland by individual PIs, allowing them to tie short-term observations into a longer history of observed signals and structure, and it improves path coverage required for inference of subsurface structure compared with that allowed by the GSN. Stations at remote sites make use of power, enclosure, and sensor installation equipment and techniques originally developed for remote Antarctic sites. Stations at populated sites with existing external infrastructure use a combination of techniques developed for the remote sites and other permanent or PASSCAL array-type stations. As for the GSN, all data from the GLISN network are freely and openly available through the IRIS DMC, in near-real time where telemetry allows.

The expense and difficulty of access to even the "easy" stations in the network means that remote retrieval of recorded data is highly beneficial. The network includes a mix of stations located in populated areas and operated from mains power with direct internet telemetry, and stations operating autonomously in remote areas. All of the stations currently return state-of-health information in near-real time. All stations record 1 sps (LH), 20 sps (BH), and 100 sps (HH) channels and most return these in real time. The remote stations which rely on satellite telemetry through the Iridium system (Figure 13 - green symbols) allow telemetry of 1 sps continuous data.

The ANET/POLENET network consists of 31 seismic stations deployed across West Antarctica and adjacent parts of East Antarctica (Fig 14). The stations are the instrumental component of the International Polar Year (IPY) ANET/POLENET science project and make use of installation techniques and equipment resulting from the two MRI awards previously mentioned.

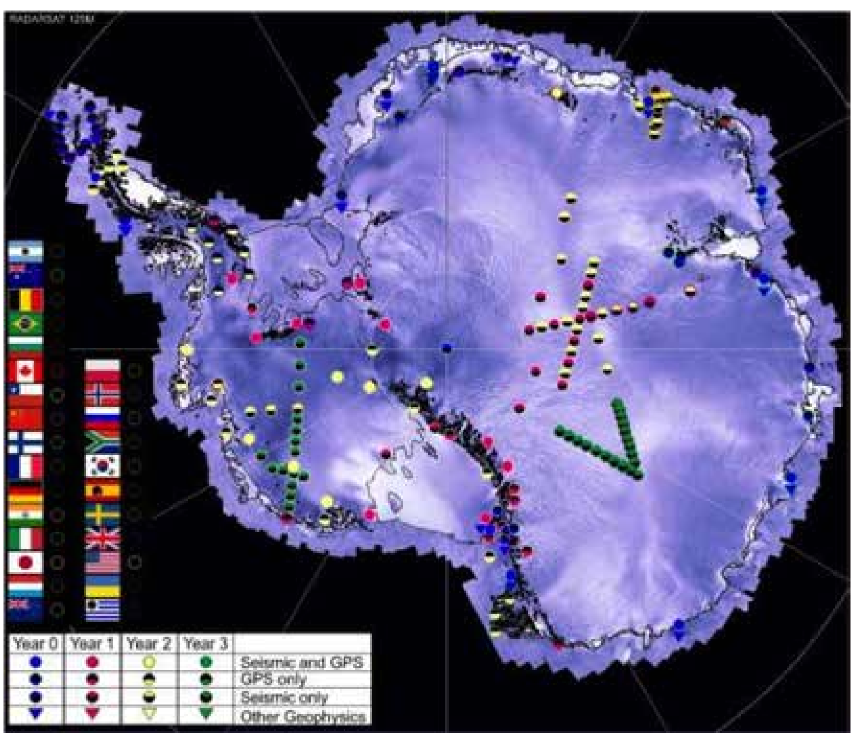

Fig 14: ANET Seismic and GPS instrumentation network.

This NSF/AES project, coordinated by lead PI Terry Wilson (Ohio State) and with seismology investigators from Central Washington University, New Mexico Tech, Penn State University, and Washington University, is a multidisciplinary investigation of the links between the solid earth and ice sheets, using seismology and geodesy as the primary tools. As an IPY project, ANET is to have a legacy, which will entail some fraction of the network remaining in place after the project has been completed.

The network originally consisted of 23 stations in West Antarctica installed between 2007-2010 under the POLENET project and 8 stations in East Antarctica that were left in place after the GAMSEIS experiment ended in 2009. A proposal to continue funding of this network for 5 years as a PI-driven science project with extensive support from IRIS and UNAVCO has been submitted. The proposal states that at the end of this 5-year science project, stations will be evaluated and ones showing optimal characteristics will be converted to a longer-term backbone network to be managed by IRIS and UNAVCO.

Most of the ANET stations are co-located with other instrumentation to facilitate logistical support. Nineteen of the stations are co-located with ANET GPS receivers and autonomous meteorology stations in West Antarctica, 3 stations are co-located with AGO (Automatic Geophysical Observatory) Space Physics observatories, and two stations are co-located with low power magnetometers.

The goals of the ANET seismological network are extremely diverse. One primary goal is to determine the crustal and mantle structure of Antarctica using broadband seismic techniques. Mantle structure will be used to develop laterally varying models of mantle viscosity that are required for glacial isostatic adjustment studies of ice mass loss since the last glacial maximum. In addition, better knowledge of the elastic moduli are needed for more accurate determinations of present day ice mass loss from the geodetically determined elastic response. Antarctic geological processes, such as rifting and mountain building have shaped glacial processes throughout the history of Antarctica, and seismology represents one of the best ways to study these processes in a continent largely covered by ice.

4.6.2 Challenges

A number of significant challenges have been identified to providing improved services for longer-term stations.

1) Site visits for remote GLISN stations are currently needed once/year for full data download. The development of full, remote data download capabilities would eliminate the need for such visits except in the case of equipment failure. Increasing storage capacity at the stations could also reduce the required frequency of site visits, but would increase the delay between data recording and scientific use of those data. Reducing the required frequency of site visits due only to the need to download data is a pressing challenge.

2) Particularly for the study of temporal and seasonal variations of geophysical phenomena, data outages on a relatively sparse network like GLISN are highly detrimental to scientific objectives. Being able to respond rapidly when problems are detected is a challenge, including during the off-season for stations in populated areas with scheduled commercial flights, and in the same or next (depending on problem timing) summer season for remote sites.

3) To improve station operations for all stations, whether they are GSN, longer-term or temporary, synergies in engineering design and logistics sharing are needed to maximize the efficient use of limited resources. IRIS and UNAVCO have established a robust and effective collaboration through jointly developing power and communications technologies, and in planning support for polar projects. Collaborations of this type provide important opportunities to address technical challenges, multi-disciplinary data collection, and long-term operational efficiency for seismic and geodetic networks. A challenge is sustaining such an interdisciplinary, inter-facility interaction in the long term as personnel change at the facilities and as facility staff try to find creative ways to juggle the many responsibilities imposed by increasing community demands. A second challenge is expanding this type of collaboration to include groups from other disciplines operating observatories in polar regions.

4) Given high deployment demands for polar engineers from the facilities, and the high costs of deployment, there is likely to be benefit in cross-training of IRIS and UNAVCO personnel on standard equipment systems. This would allow for engineers from one facility who are nearby to respond to problems with stations from either facility, reducing logistics demands due to additional personnel deployments. Finding time and resources to permit the cross training of IRIS and UNAVCO staff is a challenge.

Recommendations

- Continue work on communications systems to allow retrieval of full bandwidth data from remote, autonomous stations
- Together with relevant governance bodies, coordinate the development and implementation of a plan for longer-term seismic station operation and maintenance for GLISN and ANET/POLENET
- Continue work to maximize data quality to achieve best scientific utility of the data stream
- Increase the level of cross training within and between the facilities
- Coordinate with logistics provider (and NSF) for development of rapid-response capability to address GLISN station problems, including outside the summer season for sites in populated areas

4.7 Temporary deployments

4.7.1 Services Provided

The IRIS PASSCAL program has developed a system for promoting the highest quality and best data return possible for temporary stations, in addition to the longer-term stations in ANET. This method includes: working closely with PIs on logistics and planning; offering training on all aspects of data collection and archiving; providing quality control for all field equipment; supporting field efforts with deployment, in-field training, huddle testing, and repair; providing software to allow PIs to QC field data; and offering data-archiving support. Each of these is critical to meeting PASSCAL's charge of supporting seismic research from field to archive.

PASSCAL supports approximately 70 new experiments per year worldwide, with ~20% of these experiments focusing on polar regions. Polar projects commonly require a level of support beyond the standard support provided to all PASSCAL experiments. Specialized polar support allows the incremental effort required for developing cold-related engineering solutions, equipment fabrication and preparation for extreme conditions, and extended field support. The polar group focuses on: 1) Developing successful cold-station deployment strategies; 2) Collaborating with vendors to develop and test cold-rated seismic equipment; 3) Establishing a pool of cold-hardened seismic stations; 4) Building an engineering exchange with UNAVCO for development and experiment support; and, 5) Creating an open resource repository for cold-station techniques and test data for seismologists and others in the polar science community.

4.7.2 Challenges

A number of significant challenges have been identified to providing improved services for temporary station deployments.

1) The current demand for polar-hardened equipment exceeds the pool of specialized equipment PASSCAL maintains (Table 4). To meet these demands, PASSCAL routinely pulls equipment from the core instrument pool (data loggers and sensors designed or tested for temperate environments) either when the impact on success is deemed minimal or supplemental funds are available to cold-harden the systems. However, the general pool is heavily subscribed and PIs can typically expect to wait up to ~2 years for equipment for an experiment of >25 stations. Unlike most EAR projects, polar projects are tightly tied to NSF logistics support and are not easily postponed. To better facilitate polar portable seismology, a larger, dedicated polar instrument pool and tighter coordination with NSF on experiment timing will be required.

2) The short turn-around time between funding and deployment for many polar projects impacts the ability of PASSCAL to respond efficiently to project needs. Much of the polar-specific instrumentation and infrastructure (power, environment controls, communications, etc.) is not commercial, off-the-shelf equipment and requires considerable time to procure, cold test, integrate and prepare for shipping to the field. Due to the limited size of the polar instrument pool and staff, the PASSCAL staff is stressed when notification and funding do not provide sufficient lead-time prior to experiment deployment. With proper lead-time, the PASSCAL facility could pro-actively prepare for upcoming deployments. This would help distribute the annual workload across the year, optimize integration and testing time and ensure maximum facility responsiveness and data return. In the end, improving data quality and return from an experiment optimizes the efficiency of the limited (and expensive) OPP logistics and science resources.

3) Challenges for the temporary pool include the maintenance of the existing capabilities and continued work on expanding the environments where this pool can be deployed. A good solution for cold, dry environments has been established and can be improved incrementally. However, the cold and wet environment of the more temperate polar regions (lower altitudes and latitudes) still lacks a robust solution. The dynamic environment of faster-flowing glaciers also lacks a solution. The areas near the lower latitudes and altitudes in the polar regions face the obstacles associated with cold and long periods of darkness, but also face the challenges associated with high snow accumulation and melt. As interest in studying the more dynam-

PASSCAL Polar Equipment	# Units
3-ch Data Logger	
Quanterra Q330	51
3-ch Sensors	
Broadband (>=120 sec)	75
Intermediate Period	6
Snow Streamer, 1 comp, 12tko, 25m	9
Broadband Station Enclosures	60
Short Period Station Enclosures	110

Table 4: PASSCAL Polar equipment pool. Not shown in the table are the hundreds of core sensors and acquisition systems that can be, and are, borrowed from the PASSCAL core pool to augment polar experiments that occur in the more temperate climates and for summer-only operations. The sensors above are fully subscribed, and PASSCAL currently has very limited ability to support new experiments without new capital investment in the pool.

ic areas of glaciers (e.g., near termini) increases, there are additional challenges associated with instrument tilt, rapidly changing station locations and orientation, and, in some cases, instrument loss due to dangerous crevassing, suggesting a need for smaller, lighter, cheaper, perhaps disposable, instrumentation. Available data logger/sensor technology exists that, with development effort, could produce the needed station package for these cold, wet environments. This technology promises to be smaller and require less power than the current seismic systems. The technological development for a cold, wet station solution could likely be folded back into the broader polar pool to reduce logistics and power requirements and afford a uniform pool for all polar environments.

4) A challenge for all of the systems is to achieve a more efficient power solution. Current solutions rely on either very expensive primary batteries, for the coldest locations, or very heavy loads of secondary batteries, for the milder, coastal locations. Continued monitoring, testing and integration of emerging battery technologies could significantly reduce station costs in both materials and logistics.

5) Real-time data acquisition continues to be a weak point of the current seismic systems. Communications are limited to Iridium satellite telemetry in remote areas at high latitudes, and, at present, single Iridium channels have insufficient bandwidth and require too much power to deliver complete real-time data from autonomous seismic stations. Such solutions are currently used mainly for state-of-health monitoring and transmission of low-sample-rate data. Continued development of telemetry solutions is required to afford transmission of real-time seismic data, to improve science utility and logistics planning.

6) As the growth in polar experiments continues, the staffing level of polar staff will also need to grow. Opportunities to leverage PASSCAL core staff remain, but as the number of experiments increases, the polar staff will need to be increased. At this point, the leveraging of the core PASSCAL staff helps with load balancing through the bi-polar field seasons, but the pre-season stress on the polar staff is quite high. This is often due to the timing of the receipt of approval on grants relative to the required ship dates to the field. If specialized equipment or enclosures are required that are not available in the polar pool, the polar personnel must fabricate, integrate and validate all field equipment in a very short period of time. This not only risks the robustness of the equipment due to the rushed timeframe, but also stresses the staff.

7) As the level of support requested by Principal Investigators and NSF of PASSCAL for short term stations increases, the need for logistic support grows. For Antarctic experiments, this is largely seen in the volume of equipment handled at McMurdo. The need is growing for larger on-ice facilities to test, repair, stage field instrumentation, and prepare the equipment for remote deployments. Items currently hindering these operations include:

a. Adequate seismic sensor testing facilities - a simple rigid but not necessarily permanent structure.

b. Increased winter-over cold storage – This would remove the need to retro functional equipment that will be utilized in the following seasons.

c. Increased workspace, including lab, office and staging areas - As the amount of equipment and staff support provided by PASSCAL increases, the need for areas to service, test, prep and stage equipment grows.

d. Easy and regular access to transportation for staff and equipment - A large amount of time is spent moving equipment and searching for transportation sources to move equipment.

Recommendations

- Establish closer coordination between NSF, the facilities, and the investigators in project planning through project award to more effectively schedule supported projects and make available the resources needed for implementation in the field
- Work with the community to develop and implement a plan for establishing and maintaining a dedicated polar instrument pool that is large enough to meet community needs
- Complete real-time telemetry development
- Develop procedures for effective evaluation of emerging technologies
- Maintain capable and well trained staff to meet the existing and future demands of NSF-OPP funded projects requiring facility support
- Acquire real-time telemetry capabilities for all remote polar stations and enhance network monitoring capabilities at IRIS PASSCAL
- Establish a geophysics facility in McMurdo for testing, preparing, and staging equipment for geophysical experiments, and improve vehicle access.

4.8 Equipment development

To ensure the polar equipment pool meets the challenges of operating in extreme environments, there has been a significant ongoing effort in equipment development and testing at IRIS. The following subsections describe briefly some significant aspects of the current research and engineering occurring within the IRIS PASSCAL polar group. All aspects of development and design performed at the IRIS PASSCAL facility are freely and openly available via the PASSCAL polar website, http://www.passcal.nmt.edu/content/polar.

4.8.1 Services provided:

Sensor systems (transducers and data acquisition systems): IRIS does not do primary sensor design work, but works with vendors to improve operational and environmental specifications to meet expanding requests for seismic observations in polar regions. As mentioned above, cold-hardening sensors has been accommodated by at least one sensor vendor (Guralp), to produce the "Cold 3T". Other products have been deployed to the ice in environments beyond the stated specifications of the instruments due to a shortfall of cold-rated sensors.

In terms of data-acquisition systems (DAS), PASSCAL utilizes the Quanterra Q330 as it is cold rated to -45C. PASSCAL also utilizes the RefTek RT130 for short-term deployments in areas that do not require cold rating. RT130s come from the general PASSCAL instrument pool, as the polar pool does not currently include any.

Telemetry systems: PASSCAL polar systems have two options for system telemetry: State of Health (SOH) and data retrieval. SOH information is transferred using Xeos modems over the Iridium network. SOH files are relatively small and can be transferred over standard Iridium data paths or over Short Burst Data (SBD) paths. Data retrieval over the Iridium based real-time telemetry system is currently being used in Greenland as part of the GLISN network. This retrieval system incorporates the RUDICS (Router-based Unrestricted Digital Internetworking Connectivity Solution) system for transferring data from the Q330 through the Xeos Iridium modems. This solution will not transmit the entire data stream, but will allow low-sample-rate data to be transmitted from the stations and will allow a much better station assessment for maintenance purposes, while also allowing science to be performed year round.

Enclosures: PASSCAL currently has several polar enclosure designs and performs custom design work when a suitable enclosure is not available. System enclosures vary in size with the duration and capacity needed for a given experiment. Insulation can also vary depending on the temperatures expected where the system is deployed. A large effort at IRIS PASSCAL has gone into trapping waste heat from acquisition systems and insulating sensitive components from extreme weather. Designs utilizing vacuum panels with extremely high R-values have been incorporated into field designs deployed to the high plateaus of Antarctica, where low temperatures reach nearly -80C, with successful system operations as a result.

Power systems: IRIS has developed and adapted various power systems to meet power budgets, logistics limitations, and funding availability to maximize station performance and uptime. A variety of systems are utilized. With an autonomous remote station, solar power is most desirable. However, solar exposure varies substantially over the range of polar deployments IRIS has fielded, so the solar PV array designs are varied. Primary and/or secondary battery types are integrated into the power systems depending on the environmental aspects of the deployment area.

Technical interchange and engineering process: To ensure that all IRIS projects follow a consistent engineering process, an IRIS wide engineering review process has been instituted. This approach establishes goals and costs for engineering tasks, allows for technical interchange among all components of IRIS Instrumentation Services, and allows for the sharing of design and development ideas across the facility. IRIS also coordinates closely with UNAVCO on engineering efforts.

4.8.2 Challenges

A number of significant challenges have been identified to providing improved services in the area of equipment development.

1) Sensor systems (transducers and data acquisition systems): Of the polar pool mentioned above, the cold-rated broadband sensors are specified to operate in temperatures down to -55C (based on the mean annual temperature at South Pole). The depth of burial of these sensors limits exposure to extreme midwinter temperatures, but even

Fig 15: Joint IRIS / UNAVCO ANET installation at Mount Patterson, Antarctica.

at 5-10 meters depth the temperatures are essentially the mean annual temperature, or about -55C for the Antarctic plateau. It is clear that, to assure continued operations in very cold regions, some environmental control of these transducers is required. Some other seismometers (Trilliums) are specified to -20C, but appear to work in much colder environments, as confirmed by cold chamber testing and field deployments. Of course, there are obvious risks in operating beyond specifications (shorter life span, potential equipment failures during mid-winter, invalidation of warranties, etc), but the current size of the cold-rated pool is insufficient to meet the demand for broadband sensors in the polar regions.

The Quanterra Q330 is cold rated to -45C, better than other available systems, but above the coldest temperatures at which PIs need DASs to work. Systems deployed in the coldest environments therefore currently require environmental protection and reutilization of waste heat to keep the DAS within operating specifications. Better cold tolerance for the DAS, and/or better solutions for cold hardening of the enclosure system, are needed.

In addition to the cold sensitivities of the current pool, PASSCAL is being asked to field more experiments in wet regions and in heavy accumulation/melt areas. The current systems are not substantially “wet-cold” hardened and more work needs to be accomplished either to make the generic pool adaptable to wet environments, or to create a subset of the pool that is specifically reinforced for temperate polar work.

2) Telemetry systems: The development of the Iridium based real time telemetry system now allows low-rate data return. Developing the capability for complete data retrieval would allow fewer station visits and allow optimization of logistics planning, as well as facilitating science activities.

3) Enclosures: Continued work on enclosures is required as designs must meet needs not only of broader polar applications (including wet environments), but also to continue to push designs into smaller and lighter packages to minimize logistics costs associated with transport and recovery operations. In addition, as new sensor, power and telemetry systems are developed and deployed, the enclosures need to be modified to incorporate new form factors, power budgets (waste heat), and operating specifications.

4) Power systems: While solar is a desirable power source, it comes with difficulties in year-round operations, primarily associated with over-winter power maintenance in low- to no-sunlight conditions. IRIS has utilized extremely high power-to-weight/volume lithium primary batteries to bridge the dark gaps, as they have very good capacity at extremely low temperatures. Unfortunately, these batteries are very expensive and one-time-use only. Therefore, although they greatly reduce logistics costs by their small volume and high capacity, the burden of expense moves from the OPP logistics budget to the science-support budget. Therefore, PIs are impacted by this cost and seek lower-cost alternatives. PASSCAL therefore continues to work on alternative power systems such as AGM-battery-based PV power and wind turbines, and continues to investigate new battery systems (e.g., rechargeable lithium) to maximize power with minimized logistics.

Engineering analysis continues on cold-rated solar charge controllers, power distribution from multiple power systems, and battery life cycle. IRIS is concerned with the life span of these systems under extreme environmental conditions. As many of our systems have been fielded for multiple years, it will soon be possible to determine the mean time between failure and help establish an amortization model for the polar pool.

Recommendations

- Improve the cold specifications for the instrumentation, especially the DAS systems. This would reduce the level of work and materials required for enclosures, and reduce the power budget for maintaining proper operations in extremely cold environments.
- Further integration of system components with SOH output to telemetry systems will allow for better pre-season planning and reduced logistics costs.
- Further development of telemetry for data retrieval would allow for better pre-season planning and reduced logistics costs and would support science activities.
- Develop enclosures for cold, wet environments.
- Improve collaborations with equipment manufacturers to enable on-demand ordering of system components
- Further development and testing of power systems to improve efficiency and capacity.
- Continue to work with manufacturers to achieve sensors and data-acquisition systems with improved cold tolerance, ease of use, ruggedness, and integration potential with non-seismic sensors.
- Continue efforts to achieve full-bandwidth data return from remote sites by telemetry.
- Improve on-site QC capability to validate proper system operation.

4.9 Governance

The dramatic recent increase in demand for IRIS support of seismological studies in polar regions makes a reexamination of governance and management structures for polar services at IRIS a critical part of planning for the coming decade. IRIS arose from an initiative of the seismological community 25 years ago, and the facility has from the beginning been a community facility, with all aspects of governance and oversight provided by the seismological community through participation in standing and ad hoc committees for the several major IRIS programs. Standing committees for the Global Seismographic Network (GSN), Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL), Data Management System (DMS), and Education and Public Outreach (EPO) programs provide community input and budget oversight for the operation of the facility; a similar committee provides guidance for the

IRIS Earthscope/USArray effort. A Board of Directors elected from the community provides governance of the facility as a whole. The facility has not had a management or governance structure dedicated to polar activities, but has obtained community input and oversight through the standing committees for the core programs and from ad hoc committees.

The PASSCAL standing committee is currently tasked with oversight of activities and budgets related to temporary station deployments, and the GSN standing committee with oversight of activities and budgets related to GLISN and GSN stations; these committees provide guidance to the PASSCAL and GSN program managers and report to the Board of Directors. Each of these standing committees also has significant responsibilities for oversight of non-polar activities, which still constitute the large majority of IRIS facility support. Two polar-specific committees also provide input to IRIS: the Polar Networks Science Committee (PNSC), a joint IRIS/UNAVCO committee, provides input on the full range of IRIS polar activities, through a non-voting liaison to the PASSCAL standing committee and through reports to the Board; and the GLISN Science Advisory Committee provides input to the GLISN project and to the GSN standing committee through a liaison, and provides reports to the Board. Coordination of polar activities within IRIS is provided by the IRIS Polar Coordinator, but budget authority is distributed across several core programs. The Polar Coordinator currently serves triple duty as the GSN Program Manager and GLISN Project Manager.

The current governance and management structure for polar activities within IRIS has developed organically, as the level of polar support provided has increased across several IRIS programs over time; as a result, the structure is complex and multi-branched. The recent increase in demand for IRIS facility support in the polar regions has reached a level where existing government and management structures within IRIS are overtaxed.

Planning for the next decade provides an opportunity to revise and streamline current structures in the context of the large and increasing demand for IRIS polar services, to ensure that polar operations within IRIS are well coordinated and reflect community needs, and to ensure a clear path forward for the IRIS facility so that funding from NSF (EAR and OPP) is well justified and optimally applied. It is important to address the pressing needs for polar management and governance in a timely fashion, as the demand for polar services continues to grow and several key issues requiring community input loom on the horizon. For example, addressing the possible conversion of temporary stations to longer-term observatories will require clear structures for management and governance.

The key needs for a polar governance structure within IRIS are (1) to provide an effective, efficient, and transparent forum for community input directly to the polar program team within IRIS; and (2) to provide commensurate budget oversight. The polar management structure (1) needs to be sufficiently clearly defined that the transmission path for community input is easily understandable; (2) to provide a well-defined and open path for communication between NSF and IRIS polar programs; and (3) to provide a clear decision-making pathway for polar activities.

In both governance and management, there remains a strong need for close coordination between the multiple programs of the IRIS facility. The ability of those parts of the facility supporting polar activities to use and draw on resources from the full facility should not be inhibited; nor should the ability of non-polar support activities to use and draw on those resources focused primarily on polar support be inhibited. Within the current IRIS structure, the key needs for governance and management for the core programs are satisfied by standing committees and program managers. Because of the need to draw on many aspects of the facility for polar support, IRIS is encouraged to think more broadly than the current programmatic structure for addressing the needs of polar management and governance. However, the identification of one individual from management and one committee with primary responsibility for addressing polar services is very strongly encouraged.

A reasonable and efficient option for improving governance and community input for polar activities would be to utilize and build on the structure of the current Polar Networks Science Committee (see Chapter 5), which is currently tasked to provide guidance on community requirements for polar facilities and to support coordination between IRIS and UNAVCO. The committee currently consists of eight members, four appointed by IRIS and four appointed by UNAVCO. The IRIS-appointed committee members could serve as an IRIS standing committee overseeing polar activities; augmentation with a fifth member could be considered if needed. Whatever solution is adopted, it must respond to the key needs outlined above.

Recommendations

- Establish a governance structure for polar activities to (1) provide an effective, efficient, and transparent forum for community input directly to the polar staff; and (2) provide commensurate budget oversight
- Establish a management structure for polar activities to (1) define a clear transmission path for community input; (2) provide a well-defined and open path for communication between NSF and IRIS polar staff; and (3) provide a clear decision-making pathway for polar activities

5.0 Improving Facility Governance, Collaborations and Efficiencies

FACILITY COORDINATION

5.1 Introduction

In this chapter, improving governance of the polar facilities through a community- endorsed committee is discussed, along with strategies for improving collaboration between UNAVCO and IRIS and for obtaining efficiencies in the polar services offered. This chapter expands on a number of the challenges identified and recommendations made in the previous two chapters. An abbreviated compilation of the recommendations can be found in the executive summary.

5.2 Governance

The Polar Networks Science Committee (PNSC), a joint IRIS/UNAVCO committee, is currently tasked to provide guidance on community requirements for polar facilities and to support coordination between IRIS and UNAVCO. The committee currently consists of eight members, four appointed by IRIS and four appointed by UNAVCO. The committee meets once a year, and the Chair and Vice-Chair positions rotate between an IRIS- and a UNAVCO-appointed committee member. The committee members report to the governance bodies of the facilities in different ways, as described in the governance sections of Chapters 3 and 4.

The PNSC was setup as an oversight committee for the 2007-2009 NSF MRI power/comms project (see description in Chapter 3), but it has transitioned to being a conduit for polar community input to the facilities with broader reach. To this end, two workshops have been organized by the PNSC (i.e., the Autonomous Polar Observing System Workshop and the Facility Planning Workshop) to engage the community in developing a vision for sustained polar networks.

There is an important role for the PNSC, or some similar kind of community-endorsed committee, to play in the governance of the facilities, particularly as the services provided to the community expand and the demands placed on the facilities by the community grow. To foster greater input, engagement with the broader community can be obtained by requesting feedback on written reports, conducting town hall style meetings at major conferences (e.g., AGU), and via other venues, such as direct contact with polar user groups. In this manner, the UNAVCO and IRIS Boards, with input from the committee, can maintain a fresh perspective on the emerging needs of the polar research community.

A key governance issue that needs community-level input is the coordination, operation, and maintenance of longer-term networks, such as ANET, GNET and GLISN. The IRIS and UNAVCO facilities have played a critical role in establishing the ANET and GLISN networks, and they constitute a resource for operating and maintaining these networks into the future. It is important for science PIs, the PNSC (or some such committee), and the facilities to develop a framework for sustained operation and maintenance of remote autonomous stations in the polar regions, not just for GLSIN or POLENET, but for other temporary networks as well that could be beneficial to the community if they were transformed into longer-term networks. The PNSC is poised to play a lead role in evaluating possible succession plans for PI-led stations and networks to longer-term operation and for maintenance by the UNAVCO and IRIS facilities.

While it is recognized that the PNSC is not necessarily inclusive of all disciplines that could be served by the current and near-term polar support plans, the PNSC, with its current structure, has sufficient depth to review and recommend steps to ensure maximum science benefits to the community. The PNSC can also function as a resource for NSF, such as in deliberations on whether to continue data collection at a critical site.

Recommendations

- Together with the PNSC and other relevant governance bodies, the facilities should develop a mechanism for evaluating the needs and possible transition plans for PI-led stations to long-term, facility-operated stations

5.3 Enhancing Collaborations

In the past, the UNAVCO and IRIS facilities grew independently, driven by the unique needs of each communi-

Fig 16: Co-located seismic and continuous GPS systems installed by IRIS and UNAVCO at Thurston Island, Antarctica. *Courtesy of Seth White.*

ty. The science priorities of these two communities in the polar regions and the technology to support those needs have evolved such that the efforts of UNAVCO and IRIS overlap much more than they have in the past. This creates an opportunity to enhance collaboration between the two facilities.

The activities of UNAVCO and IRIS in the polar regions have grown such that their presence in McMurdo and their use of air support and logistics are significant enough to warrant revisiting the relationship between UNAVCO and IRIS and the logistics support contractors. Up to this point, UNAVCO and IRIS have been viewed as a "Science Event" and treated the same as every other science group. Yet, at present, the role they play is not equivalent to a science group but is rather similar to a science support contractor providing services for science groups. This leads to a number of questions: 1) Is temporary Crary Lab space the best space in McMurdo for IRIS and UNAVCO to work on equipment? 2) Should IRIS and UNAVCO be involved earlier in aviation planning to maximize efficiency in maintaining remote instrumentation stations?

The collaboration and communication between IRIS, UNAVCO, NSF-OPP, research PIs, and the science support contractor are critical to the success of polar research. Often, PIs must act as a go-between amongst the different organizations because individuals in each facility have not communicated details or decisions to each other. This can lead to delays in project planning and stress on all participants. As a whole, better communication between the different polar organizations would improve collaboration.

5.4 Example of Past Collaborations

5.4.1 Collaboration Initiated by Scientists

ANET is an excellent example of UNAVCO and IRIS working together toward overlapping science objectives and technology. By collaborating at the outset, UNAVCO and IRIS were able to create efficiencies in design and field deploy ability of autonomous systems that resulted in co-locating seismic and GPS instrumentation throughout Antarctica (Fig 16). This cooperative effort enabled efficiencies in design, data retrieval, and trained personnel while providing for greater instrumentation density at hard-to-reach locations.

5.4.2 Collaboration Initiated by UNAVCO and IRIS

With more researchers striving for year-round data collection in remote polar regions, NSF recognized an opportunity to encourage shared knowledge and cooperation between the seismic and geodetic communities in fielding autonomous systems capable of long-term operation. To this end, an MRI project (described previously in Chapters 3 and 4) was initiated for design of power and communication systems for remote polar deployment with IRIS and UNAVCO as key players. This collaboration led to advances in polar power and communication, and the improved equipment has been successfully fielded in Greenland and Antarctica. The technology developed by this effort has been rapidly adopted by the broader polar scientific community to field reliable power and instrumentation platforms in the Arctic and Antarctic, as illustrated in Figure 17, where an automatic weather station is being installed using the MRI-developed power system.

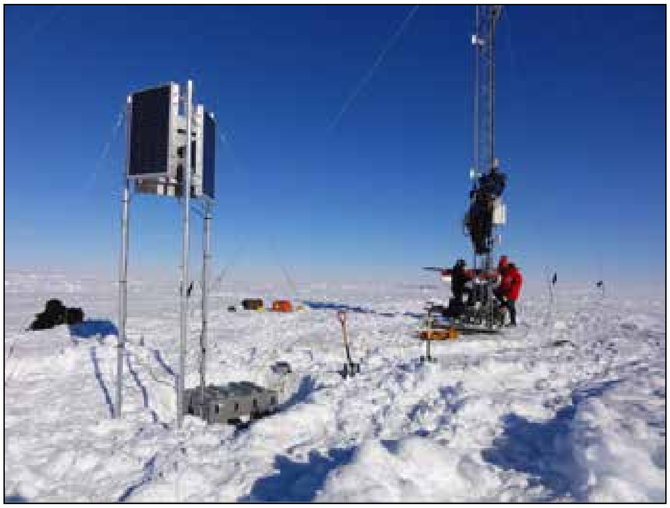

Figure 17: University of Wisconsin AWS tall-tower installation using a UNAVCO platform to provide year-round power for the instrumentation. *Courtesy of Marianne Okal.*

5.5 Strategies for Improving Future Collaboration

Collaborations between UNAVCO and IRIS generally have three goals: enhanced science, improvements to common technologies, and efficient use of limited resources (e.g., funding, equipment pool, and access to sites of interest). ANET and GNET were driven by a collaboration built around the synergy of co-existing (and often co-located) GPS and seismic instrument networks in Antarctica. The MRI collaboration to develop a common power and communications platform harnessed the considerable past experience of both UNAVCO and IRIS to improve the associated technology. These improvements led to more efficient use of limited resources. Future collaborations should focus on similar technology improvements that enhance the value of the science obtained.

5.5.1 Common Power/Communication Platforms

A natural direction to continue the improved technology developed by the power/comms MRI is to work towards a modular and scalable common power and communications platform that can facilitate multiple instruments. A second goal is to work towards lighter weight instrumentation packages with reliable power. The environments across the polar regions vary sufficiently that a single power package will not satisfy all needs, but there are enough commonalities among site needs that a common platform would be able to satisfy most requirements.

The range of needs based on environmental conditions include:

- Sufficient power to deploy at sites with long winters but modular to scale-down to lower latitude sites,

- Light-weight to be deployed by helicopter for sites that are otherwise inaccessible,
- Able to accommodate high snow accumulation (up to meters per year) and wet summer conditions,
- Able to survive extreme cold and high winds.

A common platform would greatly benefit the many polar scientists that use both GPS and seismic instrumentation. The ability to add an additional instrument or two would allow science teams to modify the system for their particular needs and enable interdisciplinary, transformative science.

5.5.2 Personnel

UNAVCO and IRIS polar personnel already take advantage of each group's knowledge and experience. There are several ways to improve the exchange of knowledge and increase cooperation for both future development and deployment of instruments. A few of possibilities include:

1) Co-locating the UNAVCO and IRIS facilities for easier collaboration and training.

2) Obtaining dedicated space in McMurdo – a "Polar Geosciences Support and Staging facility", which would be shared between IRIS and UNAVCO.

3) Creating shared internships for younger geoscientists that would also relieve some of the pressure of intense field schedules for field engineers.

4) Planning regular collaborative workshops between IRIS and UNAVCO engineers to review successes and challenges of various technology development and deployment efforts. These workshops should include representatives from users within the scientific community.

5) Cross training of field engineers to deploy/repair instruments from both organizations. Field engineers are one of the resources that limit deployment and maintenance of instruments. Cross training would not only increase the efficiency of deployments but would also increase the sharing of knowledge between the two organizations.

6) Ensuring communication regarding funding, planning, and support between all polar organizations including NSF-OPP, IRIS, UNAVCO, PIs, and the science support contractor.

5.5.3 Science

Similar to ANET and GNET, future scientific collaborations are expected to lead to collaborative deployments that will involve both UNAVCO and IRIS. UNAVCO and IRIS can help stimulate these collaborations by providing a forum for scientists to exchange ideas about regions and sites of interest as well as about important scientific questions. The format for this could be an annual workshop, virtual on-line workshop, or online discussion forums. Using such a platform, UNAVCO and IRIS can help encourage multi-disciplinary, multi-PI projects that maximize scientific value, efficiencies of logistics, field seasons, and collaboration on data and other results.

Recommendations

- Increase the level of cross-training within and between the facilities
- Continue close collaboration to improve power and communication systems for continuously operating stations
- Foster and support collaborations with other polar science communities to advance mutual goals of improved data return and of quality from multi-sensor stations

5.6 Improving Efficiencies

While the collaborations described above will lead to more efficient use of resources, each organization can also improve internal efficiencies. These include both logistical and organizational planning and also improving communication and documentation with each science group.

5.6.1 Modular, Scalable, Common Power and Communication Platforms.

Improving power and communication technology for remote field deployment is a theme throughout this chapter because it impacts all aspects of maximizing science while minimizing resource use. The power/comms MRI made significant improvements in the power systems currently in use by both UNAVCO and IRIS but there is still room for further improvement. Recently, more co-located seismic and GPS stations have been deployed, but the systems are still completely separate in terms of power and communications. Advantages of common support systems are that they would be more reliable (shared engineering effort), they would share common parts, they would reduce the need for cross training, and they would require similar tools for installation and maintenance of each sensor system. Such power and communication platforms would also offer greater accessibility within the broader PI community for proven "off-the-shelf" remote instrumentation capability.

In terms of resource use, advances in battery technology and power management can mean the difference between an acceptable dataset and one that will provide transformative science results. It also means the difference between one helicopter flight or many. There are a number of approaches that will contribute to improvements, and the system as a whole will benefit from advances in all of the following:

1) Collaboration with other groups designing power and communication devices for long-term installation to glean the lessons learned. For example, the University of Wisconsin AWS systems or NSIDC's AMIGOS systems have proven successful. IRIS and UNAVCO can learn from them while also sharing their expertise.

2) Ensuring that the power systems are taking advantage of the most advanced battery technology available for a reasonable cost. The tradeoff between battery weight and cost may be different for each site; a modular power/communication platform that can accept different battery types would be most useful.

3) Maximizing solar and wind capabilities. Again, these will be different for each site but ensuring that the system takes advantage of the most advanced technology possible for the cost is valuable.

4) Tailoring communication strategies can also improve efficiencies. A flexible modular platform could accommodate multiple data transmission strategies.

5.6.2 People

Cross training of field engineers, scientists, student interns, and possibly even FSTP (Antarctic Field Safety Training Program) mountaineers is an easy way to improve efficiency for co-located deployments and maintenance, especially for remote installations. Each field team must have at least one individual who is technically savvy enough to perform detailed troubleshooting of all equipment on-site. Cross training can occur before the field season at the UNAVCO or IRIS facilities but can also occur during the field season. Downtime in the field or in McMurdo can be used to provide additional cross training and exchange of technologies and ideas.

5.6.3 Site Selection

As mentioned previously, improving the collaboration and exchange of ideas among scientists can result in collaborative projects or sharing field logistics for common remote sites. UNAVCO and IRIS can help facilitate communication among scientists at the pre-proposal stage, especially for deployment to new remote sites.

5.6.4 Experiment Planning and Execution

In both the pre-proposal and pre-deployment planning stages, improvements in documentation (including version control) and access to documentation would help make the planning process smoother and more efficient. The lead time between an award made by NSF and the field deployment required for that award can sometimes be as little as three months. This leads to a spike in activity and less flexibility in the field preparations. Although for some projects this might be unavoidable, for others, efforts on the part of NSF and the PI to increase this lead-time will improve the pre-field planning and design process. Adopting a four or even five year award length for complex field projects would seem to be warranted.

Further, if documentation from one project is available for other projects, this would help the process of knowledge transfer among projects and learning from successes and challenges of each system design and deployment.

5.6.5 Logistics

Although the logistics are different for each site, there are ways to greatly improve the efficiency of deployments and maintenance of many locations. The largest "hub" of UNAVCO and IRIS work is McMurdo Station.

1) Currently, UNAVCO and IRIS use space shared with all science projects in Crary Lab. This area is often crowded with limited space for staging and testing instruments. UNAVCO and IRIS have moved beyond their role as small science events. We suggest a "Polar Geosciences Support and Staging facility" in McMurdo that would be dedicated to UNAVCO and IRIS. This facility would provide space for testing equipment, staging field deployments, training scientists or other personnel (such as FSTP), and storing instruments, tools, and equipment that do not need to be returned to the main UNAVCO and IRIS facilities over the winter. It is also possible that the AWS team would benefit from inclusion into this facility.

2) Because field engineers from both organizations regularly visit various sites for maintenance as well as new deployments, having them involved upfront with aviation and resource planning within the USAP for each season would greatly improve the efficient use of human and equipment resources. This also includes working with AWS teams to improve deep field forecasting and weather station coverage.

Recommendations

- Engage with NSF to improve workspace for testing, staging, and long-term storage of equipment at field logistics hubs, particularly at McMurdo Station

Maintenance visit to GNET cGPS Station "TREO" in South East Greenland - *Courtesy Jeremy Miner.*

APPENDICES

Appendix A: References

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Appendix B: Polar Facility Planning Workshop Agenda

Thursday, September 8:

Continental Breakfast 8-8:30 am

Opening Plenary session 8:30 am

Introduction/Welcome (15 min): Andy Nyblade and Carol Raymond

NSF presentation – OPP to articulate the need for this plan (20 min): Alex Isern

IRIS polar facilities review of how things are done now (20 min) – Kent Anderson, James Gridley, Bruce Beaudoin, Tim Parker

UNAVCO polar facilities review how things are done now (20 min) – Chuck Meertens, Bjorn Johns, Seth White, Joe Pettit

Science talks (what is the future of the field and why does the science need facility support? Review of science from the APOS report)

Geodesy (30 min) – Leigh Stearns (glaciology), Ian Dalziel (tectonics)

Break 10:15-10:30 am

10:30 am Science talks continued

Seismic (30 min) – Doug Wiens

Breakout session 1 11:00-12:30: Instrumentation – What is needed to support the science?

A: Geodesy – Bob Smalley/Sridhar Anandakrishnan
- Permanent GPS stations
- Temporary equipment pool (GPS, LIDAR, others?)
- Equipment development

B: Seismic – Rick Aster/ Shad O'Neel
- Permanent stations
- Temporary equipment pool (BB, SP, others?)
- Equipment development

Lunch: 12:30-1:30 pm

1:30- 2:30 pm Reports back to plenary session (30 min per group) with a discussion on identifying areas of collaboration/coordination

Breakout sessions 2 2:30-4 pm: O&M logistics – What is needed to support the science?

A: Geodesy – Paul Winberry/ Slawek Tulaczyk
- Permanent stations
- Temporary deployments

B: Seismic – Meredith Nettles/Audrey Huerta
- Permanent stations
- Temporary deployments

Break 4:00-4:20 pm

4:20-5:20 pm Reports back to plenary sessions (30 min per group) with a discussion on identifying areas of collaboration/coordination

Friday, September 9:

Continental Breakfast 8-8:30 am

Breakout session 3: 8:30-9:30 am Personnel and more - What is needed to support the science?

A) Geodesy – Gordon Hamilton/Chuck Meertens
UNAVCO personnel

B) Seismic – Doug Wiens/Bruce Beaudoin
IRIS personnel

C) What could/should the facilities do to support polar science and interact with other related science communities collecting data from remote polar stations? Andrew Gerrard/Bjorn Johns/Kent Anderson

9:30-10:30 am Reports back to plenary sessions (20 min per group) with focus on identifying areas of collaboration/coordination

Break 10:30-10:45 am

Breakout session 4: 10:45-12 pm Governance and Coordination – What is needed to support the science?

A) Governance – Andy Nyblade/Carol Raymond
- IRIS
- UNAVCO
- Joint oversight of facilities – role of PNSC?

B) Identify efficiencies in logistical support, equipment development, equipment maintenance, field personnel etc; Develop model(s) for collaboration. – Tim Parker/Joe Pettit/Paul Winberry

Lunch 12-1pm

1-2 pm Report back to plenary sessions (30 min per group)

2-4 pm Review sections of facility plan, wrap up and writing assignments

Adjourn by 4 pm.

Appendix C: Polar Facility Planning Workshop Attendees

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