APOSreport

Autonomous Polar Observing Systems Workshop

Executive Summary

The NSF-supported Autonomous Polar Observing Systems (APOS) workshop, held at the Bolger Center in Potomac, Maryland on September 30- October 1, 2010, brought together 78 polar investigators, engineers, and technical and logistical experts to review the scientific motivations and discuss measurement requirements for instrument deployment and data collection at high latitudes. A particular focus of this workshop was the need for measurements in remote regions devoid of the infrastructure to support traditional instrumentation programs.

Polar landmasses, ice sheets, and sea ice provide unique observing platforms for research in many fields, including geodesy, meteorology, seismology, glaciology, and space physics. Areas of high interest include ice sheet stability and its effects on sea level rise, ice shelf melt and breakup, sea ice variability, glacial/oceanic interactions, the evolution and geophysical state of the mantle and crust, solar wind energy, mass and momentum coupling in Earth's magnetosphere and upper atmosphere, postglacial and tectonic deformation, and the fundamental processes and evolution of the core and terrestrial magnetic field. Polar regions play a crucial role in these and other fields, but continued scientific advances will require coordinated data collection at increasing numbers of locations in order to probe key dynamical processes at the required spatial and temporal scales. Understanding some of these processes requires data-collection systems that can function unattended for several years or longer.

Polar landmasses, ice sheets, and sea ice provide unique observing platforms for research in many fields, including geodesy, meteorology, seismology, glaciology, and space physics.

Optimizing the scientific productivity of data collection and science in these remote regions will require a new generation of cost-effective autonomous instruments with improved capabilities and greater sophistication. Development of the necessary power, communication, instrumentation, and packaging/deployment system components can be significantly advanced through expanded and sustained collaborations among the scientific community. Building and sustaining these collaborations will require expanded and new forums and structures. International strategies that should be considered where appropriate include:

1) "Supersites," which are locations where many researchers could share logistics and on-site capabilities, and where support personnel would have the training to meet the needs of multiple science groups.

2) Improved early planning and subsequent coordination of field camps and traverses.

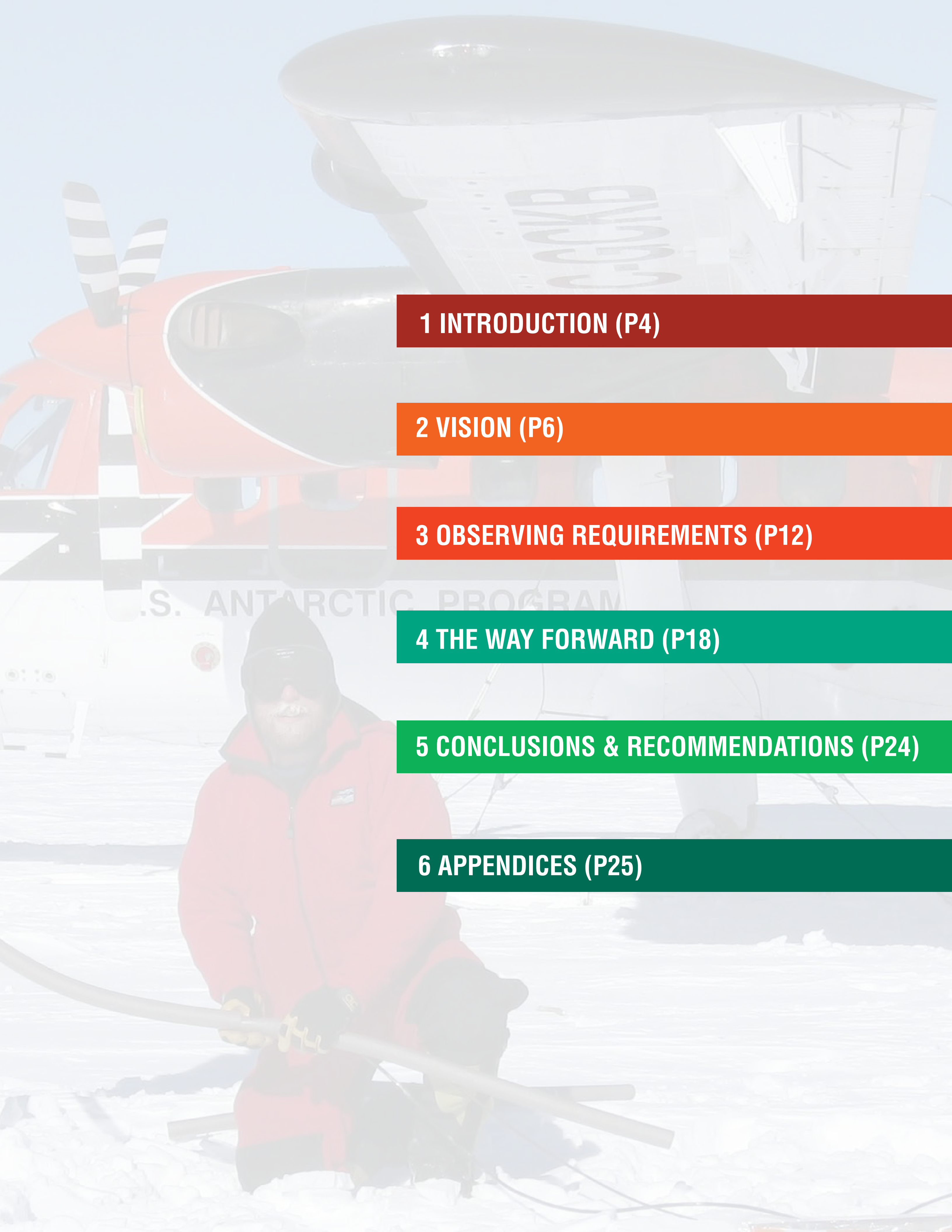
3) Establishment of a comprehensive, accessible, and up-to-date international database of past, present, and future polar deployments and associated logistical resources.

4) Timely publication (e.g., web) of updated "best practices" information on power, communications, and other polar instrumentation subsystems.

5) Establishment and encouragement of interdisciplinary working groups to advance common goals.

6) Continued support for community conferences with agency, researcher, and instrumentation consortium participation in this area.

7) Establishment of student intern and other opportunities to engage science and engineering students in these activities.



1 INTRODUCTION

FIGURE 1: Andrew Lloyd, a Penn State graduate student, servicing an Antarctic seismograph site for the POLENET/ANET project. Operating instrumentation in polar regions poses numerous logistical and environmental challenges for both equipment and personnel.

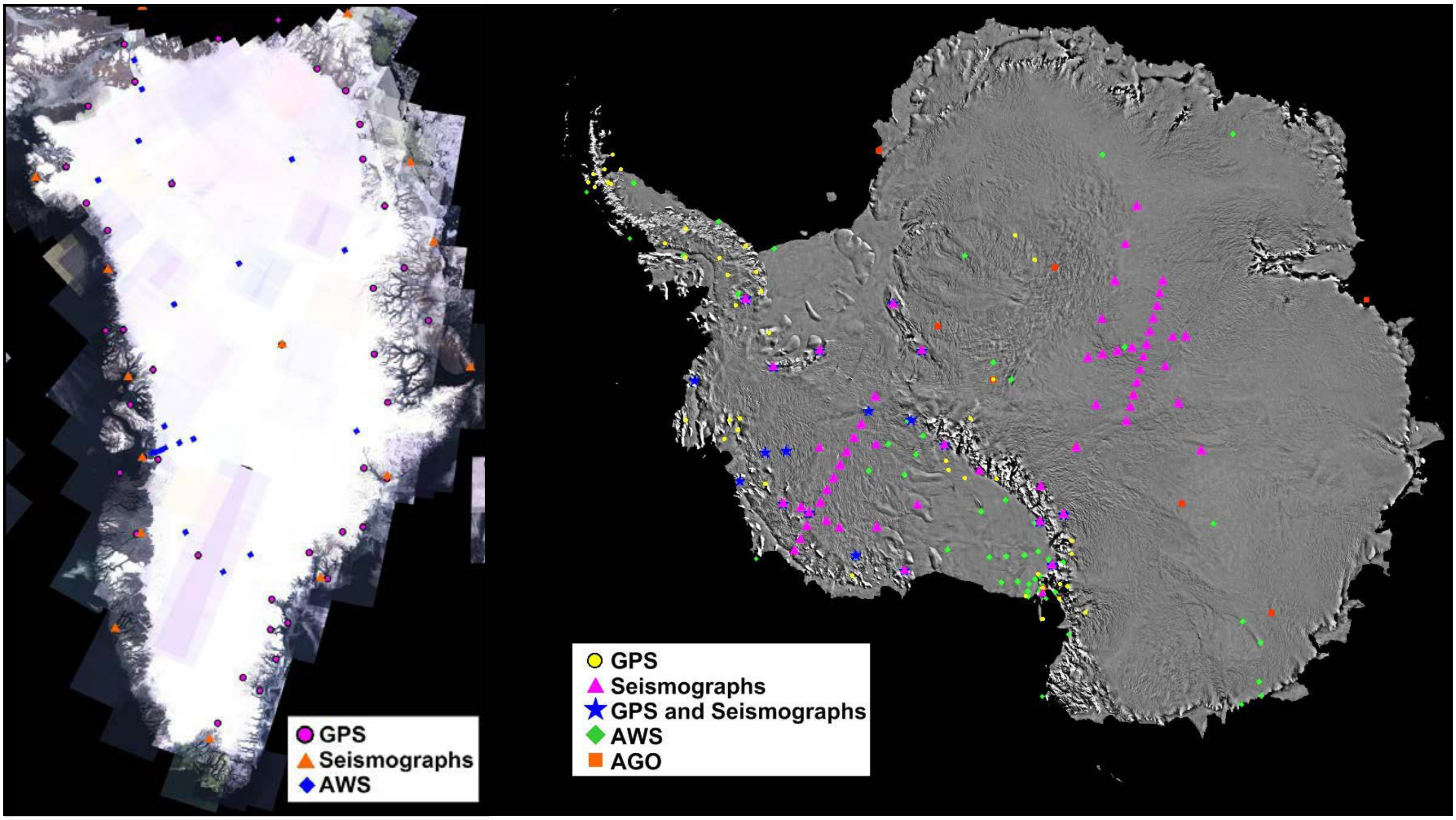
Polar landmasses, ice sheets, and sea ice provide unique observing platforms that support research in many areas, including geodesy, meteorology, seismology, glaciology, and space physics, and many important studies can only be undertaken from high latitudes. The polar regions play a crucial role in these areas of research, but continued advances require coordinated measurements at many locations to probe dynamical processes which occur on a wide range of spatial and temporal scales. In particular, progress in many fields requires sampling at much greater temporal and spatial scales than has been feasible to date.

Until recently, only a few staffed stations were adequately instrumented to explore many of the outstanding questions in polar geosciences. However, recent progress in the design and installation of autonomous ground-based polar observing systems has permitted increasingly reliable and sophisticated observations to become routine components of diverse scientific programs. Instrumentation that supports research in many scientific fields can now be deployed and operated autonomously year-round, even in the coldest and most remote regions of the polar ice sheets and mountain ranges. These advances are significant for measurement programs throughout the Antarctic continent and in remote Arctic regions. Expanding and maintaining these systems, however, requires sustained resources, and greater cooperation and coordination among different scientific research communities in order to exploit these systems most effectively.

The NSF-supported Autonomous Polar Observing Systems (APOS) workshop, held at the Bolger Center in Potomac, Maryland on September 30-October 1, 2010, brought together polar investigators, engineers, and technical and logistical experts to discuss science justification and measurement requirements (see appendices for workshop program and participants). The workshop began by highlighting some of the fundamental science questions that are currently being addressed by polar observing systems and the emerging needs of the various scientific communities. In addition, the state of the art in the design and deployment of equipment in polar conditions was reviewed, with emphasis on the commonalities in approaches from many fields. The workshop further explored new and emerging technologies that could significantly improve autonomous observing systems. A strong emphasis was the need to identify strategies for maximizing the scientific return from autonomous field sites. Finally, the workshop discussed approaches for improving communication about and coordination of field operations, instrument development, and deployment to achieve savings by sharing technical and logistical knowledge. Such savings could be directed towards future scientific measurement programs.

The workshop conclusion, articulated in the following pages, is that the polar research communities must work together to identify scientific, logistical, and technical synergies so that resources can be used most efficiently to build and deploy future generations of observing systems. Part of the solution is to improve communication between researchers, so that technical developments and engineering accomplishments are shared. Another part of the solution is better coordination during the planning of observing systems, so that development costs and logistical infrastructure can be minimized and resources shared among multiple communities. The latter parts of this document contain recommended strategies to improve communication. Finally, advances in new technologies will play a significant role in polar observations and in how those data are retrieved from the field. Polar researchers need to stay abreast of these developments and help direct advances that could benefit their science.

FIGURE 2: Maps of Antarctica and Greenland showing the locations of autonomous sensor networks installed or operated since the beginning of the International Polar Year in 2007. Autonomous sensors are now installed and operated year-around throughout vast areas of both ice sheets, recording vital glaciological, geodetic, meteorological, seismological, and space physics data.



2 Vision of a Polar Observing System – Answering the Big Science Questions

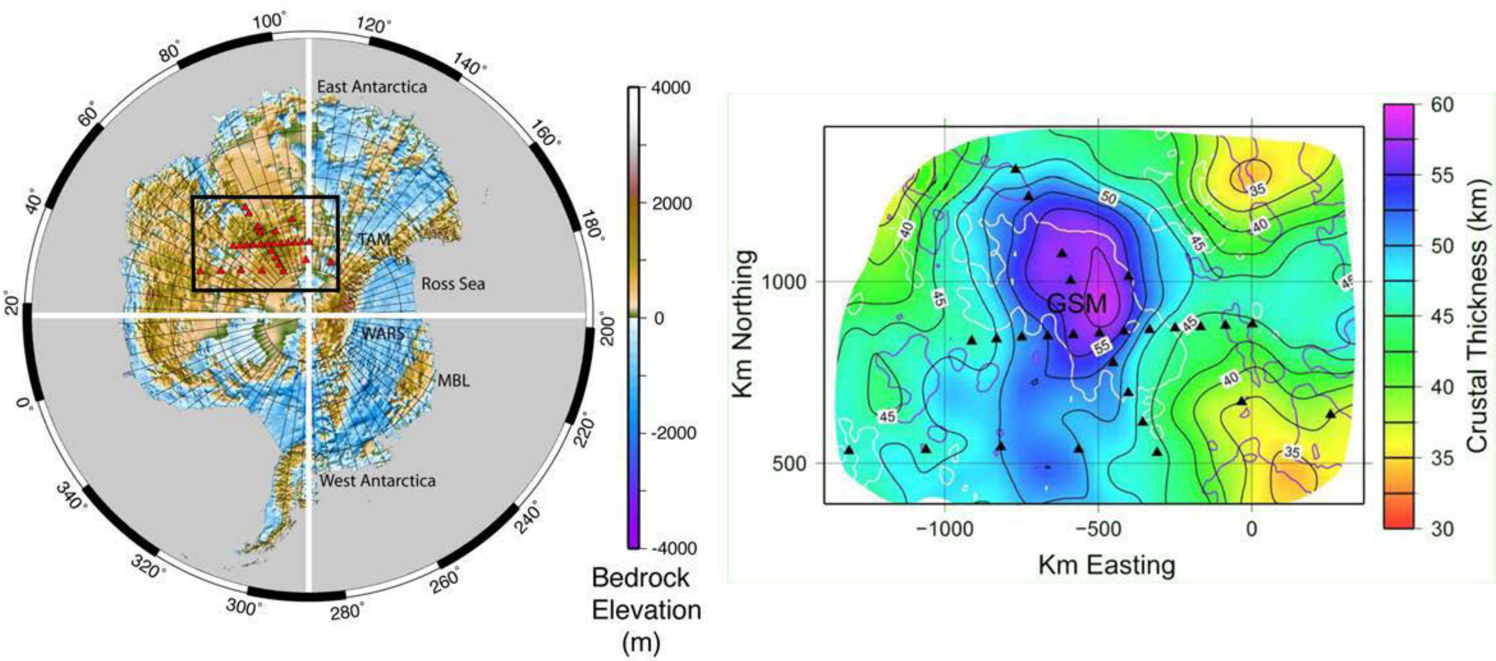


FIGURE 3: (left) Map of Antarctica with the box centered on the Gamburtsev Subglacial Mountains (GSM). The TransAntarctic Mountains (TAM), West Antarctic Rift System (WARS), and Marie Byrd Land Dome (MBL) are labeled. Triangles denote seismic stations. (right) A crustal thickness map of the GSM, showing that that this is an ancient mountain range supported by thick, buoyant crust. Triangles denote positions of IRIS PASSCAL autonomous seismographs deployed from 2007-2009 (figure courtesy of D. Heeszel and S. Hansen).

The science conducted at the Poles has global implications that affect people all over the planet. Many of the research questions address global environmental change, including ice-mass loss and corresponding sea-level rise, the role of polar processes in affecting climate, and possible terrestrial changes linked to solar cycles. Other topics include "space weather" and its important implications for satellite missions, communications, and the Global Positioning System (GPS).

Because of the wide diversity of topics and fields represented, the workshop did not seek to formulate a detailed science plan spanning all the disciplines, but rather chose to identify a number of principal scientific questions that drive the need for autonomous polar observation capabilities. In the following sections we present brief summaries of these scientific questions.

2.1 Solid-Earth Geodynamic Evolution of Polar Regions

Polar continental regions represent key elements of the global plate tectonic circuit and contain cratonic cores that have been a part of this system since early in earth history. They also determine the topography, heat flow, and hydrology which controls polar glacial and meteorological systems' evolution through recent Earth history. However, the geological, geophysical, and tectonic history of these regions is poorly understood. Antarctica and Greenland constitute climatologically key regions where Earth's major ice sheets interact with both ongoing geodynamic processes and inherited tectonic features.

Key questions include:

- The role of topography, heat flow, geomorphology in the initiation and dynamics of ice sheets
- Lithospheric and upper mantle properties and their influence on glacial isostatic adjustment
- The origins and history of major mountain ranges
- The history of tectonic extension and volcanism in West Antarctica and its influence on ice sheet development
- Role of the Iceland mantle plume in Greenland tectonic and glaciological history.

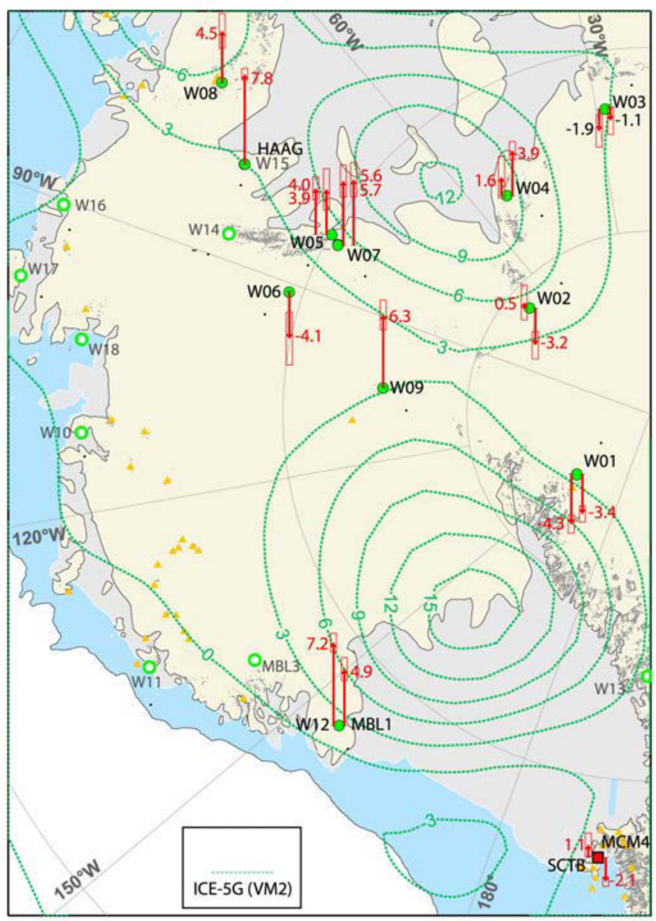
Due to the size and thickness of the Antarctic and Greenland ice sheets, little is known about the geologic composition and tectonic history of Antarctica and Greenland, except around the continental margins and along some mountain fronts where outcrops are exposed. Thus geophysical observations from autonomous observatories are one of the few methods available to constrain the present structure and past evolution of these important 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 autonomous seismographs deployed during the International Polar Year (2007-2009) have recently revealed that the lithosphere beneath the mountains dates back to the Precambrian (> 550 Ma), and that the elevation of the mountain range results from buoyant, thickened crust. This shows that the mountains that predate Earth's 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 around 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 autonomous seismographs, show very slow upper mantle velocities beneath the WARS that suggest continued mantle-driven tectonism. 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.

Key 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 in the East Greenland Caledonides during the early to mid-Proterozoic. The inland extent 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 heat flux through the lithosphere. The nature of the hotspot interaction with Greenland is unknown, and can only be addressed under 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.

Geodynamic processes in Antarctica and Greenland have strongly influenced the history and evolution of polar glaciation and climate through 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 heat flow, water conditions, and 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 lead to the formation of subglacial lakes. Since these parameters cannot be measured directly in most places, seismic and radar images provide a remote sensing method to ob-

FIGURE 4: Observed vertical velocity from campaign GPS and autonomous GPS stations in West Antartica compared to the predictions of ice model ICE-5G (Peltier, 2004). Open green circles show sites where existing data are insufficient to constrain uplift. GRACE satellite measurements of ice mass loss require correction for glacial isostatic adjustment. The misfit between the ice model predictions and observed uplift indicate the necessity of revising ice mass estimates with improved mantle rheological models. Figure modified from Bevis et al [2009]



tain information that is vital to understanding ice sheet stability. Seismic tomographic images further provide unique constraints on lithospheric viscosity and on thermal structure, which controls basal heat flow.

Geodetic measurements from ground-based GPS are vital for constraining glacial isostatic adjustment models and thus ice mass history and current ice mass loss measurements. Both the viscoelastic response, constraining mass change since the Last Glacial Maximum, and the elastic response that results from mass change of the crust and mantle within the last few decades, can be modeled from continuous GPS measurements. Understanding the glacial isostatic adjustment correction to GRACE and other gravity-derived satellite mass loss measurements is essential for constraining ongoing ice mass loss. These ice mass change estimates will allow better estimates of ice cap evolution and of the Antarctic and Greenland contribution to global sea level change.

2.2 Ice Sheet Mass Balance from Past to Future

Sea level rise from enhanced ice sheet discharge 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, because 600 million people live in coastal zones. Sea level change over the last century, due to thermal expansion of the ocean, enhanced river discharge, and diminishing glaciers, permafrost, and aquifer-discharge has led to a net global sea-level increase of 1.7 ± 0.5 mm yr^{-1} (IPCC, 2007). The rate of sea level rise increased to 3.1 ± 0.7 mm yr^{-1} in the past decade, and is projected to increase to ~4 mm yr^{-1} by 2090 under current emissions scenarios (IPCC, 2007). Because ice sheets are the largest potential source of future sea level rise, there is great urgency to understand their dynamics in a changing climate.

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 to climate warming (IPCC, 2007). Until recently, conventional glaciological theory was that large ice sheets respond slowly (timescales of $>10^3$ years) to changes in external forcings (such as air and ocean temperature, precipitation, and sea level). Recent observations of large climate-driven changes in ice sheet and glacier flow speeds in parts of Greenland and Antarctica challenge this conventional wisdom and point to the need to include these effects in sea level predictions.

Key questions include:

- Dynamics of flow and mass balance from daily to decadal time scales, and their impact on sea level.
- Interactions of air and ocean temperature with ice shelf stability.
- Ice shelf configuration and glacier flow speed relationship.
- Role of the basal boundary in the flow of glaciers and ice sheets.
- Subglacial hydrology, the formation of lakes and the role of lakes in ice sheet dynamics and as a reservoir for ecosystems.

In the past decade, Greenland and Antarctica both 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 largely attributed to changes in the flow configuration of several large outlet glaciers. Observations of thinning, retreat, and acceleration are detected along most glaciers with negative mass balances, but the mechanisms triggering these changes are not well constrained. 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 better constraints on sea level rise requires better ice-sheet models and an improved understanding of the physics governing outlet glacier flow variability. Ground-based instruments, with the capability of measuring ice flow changes at a range of spatial and temporal scales, are necessary for improving our understanding of glacier processes, and constraining ice sheet models.

2.3 Polar Atmospheric Processes and Climate Change

Climate change is one of the most important issues of our time. To understand it and its impacts, critical areas of study are required to comprehend the underlying atmospheric processes. Basic meteorological observations of temperature, pressure, humidity, and wind are essential quantities that help us understand the linkages between polar and lower latitude climate. Teleconnections of atmospheric phenomena play an important role of tying the global system together, climatologically and meteorologically. The polar regions are fragile and sensitive. They are witnessing the results of a changing climate: shrinking sea ice extent, warmer air temperatures, and ice sheet mass loss. Autonomous meteorological observations are essential to capture atmospheric behavior, and to reveal the atmosphere's un-

FIGURE 5: A new University of Wisconsin-Madison Automatic Weather Station (AWS), located at Elaine Site on the Ross Ice Shelf, Antarctica, measures temperature at two levels, atmospheric pressure, relative humidity, relative snow accumulation, solar radiation, wind speed and direction. The AWS systems have provided reliable meteorological data on very low power budgets and infrequent servicing visits.

derpinnings.

The Arctic is warming faster than the rest of the globe on average, and climate model predictions show the largest model-to-model variations in the polar regions. Clouds are one of the largest sources of uncertainty in climate models. Measurements of cloud characteristics and cloud properties are essential quantities. Data for evaluating model simulated clouds is lacking, especially in polar regions where typical satellite cloud retrievals are difficult and incomplete. Some of the major questions regarding clouds include:

- How do the macro- and micro-physical properties of polar clouds vary seasonally in the polar regions?
- What are the conditions under which polar clouds form?
- What determines the phase of cloud particles?
- How are cloud properties influenced by local and regional meteorological variables?
- How do clouds influence radiative fluxes?
- How might parameterizations of polar clouds be improved in numerical weather prediction and climate models?

The radiative behavior of the atmosphere is a critical climate parameter that reflects integrated changes in the overlying atmosphere. As crucial as radiation observations are for evaluation of model simulations, high quality, autonomous radiation observations in the polar regions are difficult to obtain and are one of the biggest challenges to meet in polar atmospheric science. Some uncertainties in atmospheric radiation include:

- What are surface radiative flux characteristics over the ice caps? Are they changing over time?
- Are radiative fluxes accurately reflected in numerical weather prediction and climate models?

Measurement of polar precipitation is extremely difficult. In particular, wind transport hinders discrimination between precipitation and drifted snow. As a result, along with a very sparse observational network, knowledge of polar precipitation relies heavily on reanalyses and models. Evaluation of model-simulated precipitation is problematic because of uncertainties in long-term accumulation maps, limited data for model validation on short time scales, and difficulties in partitioning "new" precipitation from wind blown/drifted precipitation.

The rise of the numerical modeling in meteorology has led to new understanding as well as improved weather and climate forecasting. Yet even in the era of sophisticated modeling, there remains a need to evaluate models on multiple scales. At smaller scales, model comparisons can be made to direct observations like those commonly obtained from an autonomous network. It is furthermore important not only to evaluate the model state but to evaluate whether the model reproduces observed relationships between variables. The atmosphere is, finally, coupled to the Earth System. Ice sheet mass balance, and atmosphere-ocean-sea ice coupling are vital areas where further study and modeling is necessary. Increased temporal and spatial measurements that can be provided by autonomous observations will be the means to a better understanding of the polar atmospheric system.

2.4 Sea-ice, Atmosphere, and Ocean Interactions

The Arctic sea ice cover is in decline. Satellite observations have confirmed a decrease in summer ice extent, a shift from multiyear ice to first year ice, and a lengthening of the melt season. Ice thickness data from submarine transects and satellite overpasses show a thinning of the ice in recent decades. In contrast, minimal changes in ice extent and thickness have been observed in the Antarctic. Satellites observations are invaluable for providing large-scale observations of change. However, additional observations are needed to understand how these changes are occurring, to delineate the relative roles of dynamics and thermodynamics and to assess atmosphere and ocean forcing of the sea ice system.

Long-term in situ observations are critical to achieving this understanding. Field campaigns provide excellent datasets, but are logistically complex and expensive. Ice-based autonomous systems provide a relatively low cost virtual presence. They can play a significant role in addressing several key sea ice scientific questions regarding the processing governing sea ice, including:

- What is the spatial variability and temporal evolution of the mass balance of sea ice?
- What are the relative contributions of the atmosphere and ocean to enhanced sea ice melt in the Arctic?
- How is the declining Arctic sea ice cover impacting atmosphere – ice – ocean processes?
- What changes occur in atmospheric chemistry during polar sunrise?
- What is the seasonal cycle of sea ice primary productivity in Antarctic sea ice?
- What are the effects of sea swell and infragravity waves at all periods on sea ice (and ice shelves) over time?.

Ice-based autonomous systems are currently being deployed to address these and other questions. These systems are contributing to an Arctic Observing Network making long-term measurements at several locations of the atmosphere, sea ice, and ocean. Sea ice temperature, melt and growth are being measured along with the thermohaline structure of the upper ocean and air temperature and barometric pressure. Fields of spectral irradiance above, in, and under the ice cover are recorded. New advances have led to autonomous measurements of atmospheric chemistry including bromine, ozone, and carbon dioxide. Sea ice surface conditions at the North Pole are being measured and continually recorded using web cameras. These stations have the ability to operate autonomously for several years, sending their data back using satellite communication links. By integrating different instruments into an autonomous station comprehensive datasets can be compiled to enhanced understanding multiple processes occurring in the ice cover. As technology continues to improve, the role and scope of autonomous sea ice based systems should expand. For example, there are opportunities to add sensors and to integrate observations with unmanned aerial systems and autonomous underwater systems.

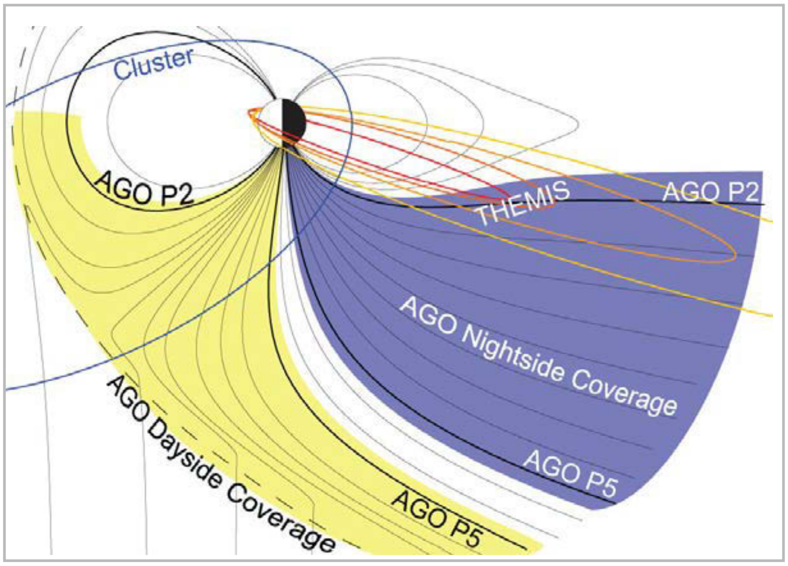


FIGURE 6. Distributed arrays, such as the AGO network in Antarctica, provide a window to study vast regions of the geospace environment. The magnetospheric regions magnetically connected to the array on the dayside (yellow) and night side (blue) are shown along with orbits of the THEMIS and Cluster satellite constellations.

2.5 Geospace and the Space Sciences

The decades since the advent of space flight have witnessed the increasing importance and relevance of the Earth's space environment. Key motivations include: understanding the functioning of planet Earth within the solar system, understanding numerous aspects of laboratory physics and astrophysics, and understanding the Sun's influence on technological systems deployed on Earth and in space. These challenges are highlighted in the 2013-2022 NRC Decadal Strategy of Solar and Space Physics (http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_056864) which emphasizes the need for coordinated, multipoint measurements in space and at many locations on Earth to probe the relevant physics which occurs on a wide range of spatial and temporal scales and to study nonlinear cross-coupling between regions previously treated as distinct. The polar regions, and especially Antarctica, play a crucial role in this research.

A prime requirement for the development, validation and operation of models is increased data with improved spatial and temporal resolution. While the goal is to produce physics based models, many processes are still not sufficiently understood and empirical relationships or parameterizations must be developed to approximate some aspects of the complex system dynamics. Uncertainties in global space weather models can be overcome to some extent by utilizing data assimilation techniques and modeling. Thus, we are driven more and more to obtain data with greater spatial and temporal resolution from a global distributed network of measurement platforms, both in space and on the ground.

The physical size of the Sun-Earth system challenges our ability to measure its dynamic variations and to capture the interactions between different parts of the system. Ground arrays of instruments at high latitudes, however, are particularly advantageous in this regard. Due to the dipole nature of the geomagnetic field, the entire outer magnetosphere maps to a relatively small region at polar and auroral latitudes. The area just equatorward of the auroral zone maps to the complex region that contains the radiation belts and storm-time ring current and where charged Alfven layers produce electric fields that contribute to the dynamics of the inner magnetosphere.

While the northern hemisphere is relatively well instrumented, the southern polar region is not because of the extreme Antarctic conditions and the lack of staffed facilities with suitable infrastructure to support the required instrumentation. However, as an observing platform, Antarctica samples a vast region of the geospace environment and provides a unique window for a number of important scientific reasons. Over the course of one day, geomagnetic field lines emanating from the southern polar-regions extend to the outer dayside magnetosphere, boundary layers and cusp across the polar cap to the mantle, lobe and portions of the plasma sheet. In addition, the geomagnetic polar cap above 80° magnetic latitude lies entirely on the continent. By contrast, the region above 80° magnetic latitude in the northern hemisphere lies mainly in the Arctic Ocean. Consequently, a distributed ground-based array in the Antarctic is the only practical way to provide near-global coverage at high geomagnetic latitudes.

Accurate measurements from the southern hemisphere are critical now to building an accurate understanding of the dynamic Sun-Earth system. Because the Earth's magnetic dipole is offset and tilted, the southern magnetic field is weaker than the northern polar field. Conductivity differences in the summer and winter ionospheres also produce electrodynamic asymmetries that must be measured and understood to build proper models. The need for increased Antarctic measurements from instrument arrays deployed in remote locations is highlighted in the recent National Research Council Space Study Board Committee on Solar and Space Physics assessment of the current status and future needs of U. S. ground- and space-based research programs in solar and space physics. The results published in The Sun to the Earth- and Beyond, A Decadal Research Strategy in Solar and Space Physics presents five challenges that are expected to focus scientific investigation during the present decade.

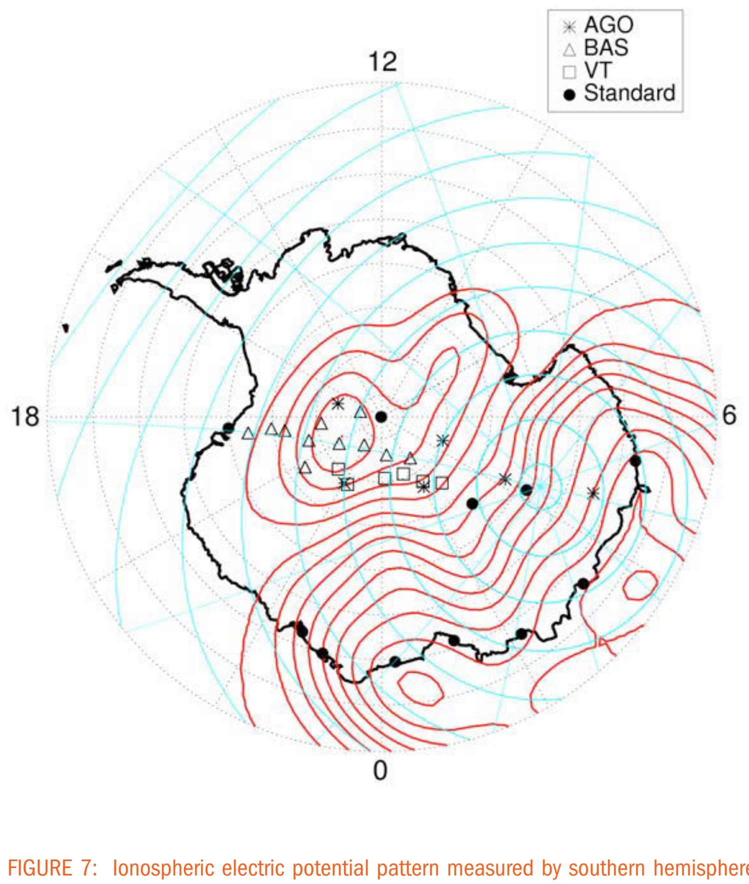


FIGURE 7: Ionospheric electric potential pattern measured by southern hemisphere SuperDARN (Dual Auroral Radar Network) HF radars on November 20, 2003 at 20:00 UT during a large magnetic storm. Dashed lines show geographic coordinate system and the blue grid shows geomagnetic coordinates. Red contours show electric potential and are drawn at 5 kV intervals. Autonomous stations are indicated: British Antarctic Survey low-power magnetometers (triangles), U. S. Automated Geophysical Observatories (stars), and Virginia Tech low-power instrument platforms (squares). Standard manned stations are shown by black circles.

3 Observing Requirements

Two of the challenges are particularly relevant to the considerations of this workshop report:

- Understand the space environment of the Earth and other solar system bodies and their dynamical response to external and internal influences.

- Develop a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in the Earth's magnetosphere and ionosphere.

The decadal report also notes the requirement for additional remote measurements at sites in the Antarctic, stating:

The relevant program offices in the NSF should support comprehensive new approaches to the design and maintenance of ground-based distributed instrument networks with the proper regard to the severe environments in which they must operate.

For the above reasons, Antarctic ground-based instrumentation has the potential to provide unique contributions to geospace studies. However, it is important to recognize that the Sun-Earth space environment is a complex, coupled system with interactions from the macro-scale (e.g. solar wind-driven magnetospheric convection) to the micro-scale (e.g. wave-particle interactions) that all contribute to the global response to energy input from the Sun and solar wind. Because of this complex interplay, proper understanding of the global behavior of one part of the system usually requires knowledge of the other parts of the system. As such, addressing some of the most stubborn outstanding questions requires a multi-disciplinary approach involving multiple arrays of ground-based instrumentation, coordinated with spacecraft and various theoretical understanding and modeling.

3.1 Required Capabilities

Polar Autonomous Observing Systems must operate without regular human intervention, and must operate over useful time periods ranging from months to many years. The various systems have a range of transducers, sampling rates, data volumes, and data latency that are sometimes dictated not by the science requirements but by available power levels.

Principal and interconnected issues associated with autonomous observations are:

- System power requirements
- Communication requirements
- Minimum temperature and other environmental robustness
- Weight and volume
- Uptime requirements
- Abilities to accommodate multidisciplinary instrumentation

Here we review general requirements for each research field, which will vary somewhat based on the type of data being collected, science goals, and specific site environmental conditions.

3.1.1 Glaciology. The goals of glaciological observing systems are to measure, understand, and model ice dynamics and processes. In particular, fast-flowing outlet glaciers and ice streams can and do change flow speeds and associated mass balance over time scales ranging from minutes to months to years. The main controlling factors are likely to be air temperature, controlling surface accumulation and melt, and ocean temperature and circulation influences on ice shelf melt and ice dynamics.

Fundamental measurements of glacial systems include flow speeds, elevation, accumulation, ice thickness, grounding line location, and changes thereof. Associated measurements of ocean circulation, temperature, and salinity (particularly beneath fringing ice shelves), sub-ice water storage and transport, and ice seismicity are additionally of substantial interest. Meteorological measurements of air temperature and accumulation are further needed. To date, GPS has been widely used to determine flow speeds. Important measurements that are planned for the near future incude TLS (terrestrial laser scanner) morphology, and basal melt-rates (remotely sensed as well as in-situ) , and temperatures (again, remotely sensed and in-situ).

Typical GPS sample intervals are 1-30s, and these data volumes are small enough to be retrieved by current satellite telemetry (often Iridium) in near-real-time, if low latency is required. Typical power required for glaciological GPS stations are ~3.5W for GPS and ~1-5W for communications. The antenna and digitizer size is approximately 30 cm (1 foot) on a side and 1m on a side, respectively, and requires a clear view of the sky. Locations are likely occupied for 1-2 years.

Other sensors (TLS, basal melt rate radar, englacial temperature, seismometers) are less generally standard. Ocean measurements (CTD - salinity, temperature, depth) encounter difficulties associated with the dynamic calving environment and iceberg scouring. Ocean environments are more challenging because of waves, winds, and increased snowfall.

3.1.2 Seismology. Seismological observations for Earth imaging and seismicity studies are generally carried out with autonomous stations that are installed for periods ranging from 2 months to 5 years. Sample rates are 20-250 Hz and data latency is ideally short, though longer latency approaching a year may be acceptable. Power consumption for non-telemetered stations is typically 1-2 W. Real time data communication, if provided, dominates the power budget, and a multi-year station would average a ~6W load for a 3 channel station returning data at 40Hz sample rates. Seismometer and digitizer stations deployed are approximately 1 m on a side, each (including a vault for the seismometer and case for digitizer). Campaign style seismic arrays deployed for a single year can use about 1.5 W per station and weigh 270 pounds with only state-of-health data returned by telemetry. Robust methodologies have been established for siting stations on either snow or rock. Spatial sensor density for specific experiments and moving arrays is typically 10s to 100s of km. For global studies and for the long-term study of polar ice and tectonic seismicity, permanent backbone networks with mean station spacing of 300-500 km (comparable to that of other sparsely instrumented continental regions) are highly desirable in both Antarctica and Greenland.

Current capability is robust for the instrumentation, but still evolving for power systems and communications. Communications capabilities are marginal for seismic data rates above 20 Hz using the single channel Iridium system presently available. The present distribution of long-term and permanent standardized seismic stations is poor in Antarctica and Greenland, though has begun to improve recently in Greenland thanks to international collaborative efforts. Seismographic instruments have also successfully been installed on tabular icebergs and on ice shelves. In such deployments, they serve not only as detectors of seismic body and surface waves and ice flexural waves arising from tectonic and cryospheric seismic sources, but additionally function as sensitive ocean wave state recorders that record a great variety of ocean signals ranging from calving "minitsunamis", to megaearthquake tsunamis, to sea swell and infragravity waves, to iceberg tremor caused by inter-iceberg collisions and shoaling. Polar seismological issues are discussed in greater detail in the SEAP workshop report (SEAP, 2003), albeit with a somewhat dated perspective.

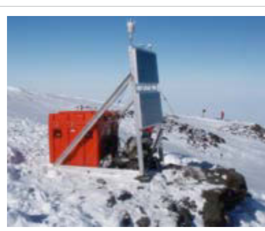
3.1.3 Geodesy. GPS measurements for tectonic and glacial isostatic adjustment studies generally require deployments of 5 years or longer to adequately resolve tectonic signals. GPS sample rates in geodetic deployments are typically ~30 s and data latency is zero/short. Power requirements are ~5 W, and sites must be located on rock. The antenna is 30 cm long and the digitizer box is less than 1cubic m. The science requires that the data collection be uninterrupted. As with seismic installations, the instrumentation and power systems are robust, with 80 – 90% data return, with some downtime due to equipment failure in harsh polar environments. Full data recovery via Iridium satellite and improvements in overall system reliability allow for multi-year autonomous operation, resulting in significant logistical cost savings. Site selection is dictated by the presence of rock outcrops and nunataks, but many potential sites in Antarctica are yet to be occupied and re-occupied. Furthermore, the weather conditions and general logistics of these isolated sites are often challenging for flight operations and for site installation/survival.

3.1.4 Space Sciences. Autonomous measurement stations used in the space sciences are generally installed for periods ranging from a few years to solar cycle time scales. Digitization time scales vary from minutes to megahertz, depending upon the instrument. Latencies of up to several months may be acceptable, but some real- or near-real time data return is required. Instrument separations vary from km scale (scintillation GPS receivers), to hundreds of kilometers (magnetometers, all-sky cameras), to thousands of kilometers (VLF). In addition GPS observations made for tectonic or other studies can be useful for ionospheric (TEC) studies, and magnetic measurements are also of interest to other communities (e.g., core studies). Weather measurements can also provide ancillary information of use to understand instrument operation. Optical measurements may provide information to supplement astronomical observations to correct for atmospheric effects. Measurements of upper atmospheric parameters may be used to forecast tropospheric behavior.

3.1.5 Meteorology. Measurements of temperature, barometric pressure, wind speed and direction, humidity, and snow accumulation, are required at both the surface and aloft for meteorological studies. Here we focus on the surface measurements (which can work in concert with other types of science data). Fundamentally, meteorological data are essential to operational forecasting as well as to weather/climate studies. At most current autonomous weather installations, sampling intervals are 1-10 minutes. Acceptable data latency is ideally zero/small for operational forecasting and months to annual for the background data. The site locations are dictated by varied meteorological considerations and are on both rock and on ice. Site density is low (10s to 100 s of km spacing), but needs distribution across

3 Observing Requirements

Table 1. Currently deployed autonomous observing systems

OBSERVATORY	EXAMPLE SITE PHOTO	POWER	COMMUNICATION	DATA STORAGE
Automatic Geophysical Observatory (AGO) (multiple sensors and instruments)		4x 120W Kyocera Solar Panels, African Wind Power (AWP 3.6), 1kW, 24V wind generator, 4x 12V 200Ah Sun Xtender, AGM Sealed Battery	IRIDIUM and ARGOS satellite communications	Onboard Flash memory
Wisconsin Automatic Weather Station (AWS)		6-12x 12V 40Ah gel-cell batteries charged by 1-2x 10 Watt solar panels	ARGOS satellite communications or 900 Mhz Freewave modem (IRIDIUM has been tested)	Onboard Flash memory (on new AWS)
Autonomous low-power magnetic data collection platform		12 VDC system, Six 40 W BP PV panels, Sixteen 100 Ah Powersonic AGM batteries, can be increased to 48 batteries, battery box is lined with 4” of Styrofoam insulation	IRIDIUM	Onboard Flash memory
Ultra-low Power ELF/VLF Receiver System		6VDC System, 90 Saft LSH20 Lithium Battery Cells	None	Onboard Compact Flash Memory
Autonomous Realtime Remote Observatory (ARRO) (multiple sensors and instruments)		4x 120W Kyocera Solar Panels, 3-5 Marlec Rutland FM910-3 Furlamatic wind turbine (low temperature build), 4, 305aH Concorde/Sun Xtender PVX-3050T AGM batteries, 8-12, 5 gallon water jugs - thermal storage	IRIDIUM	Onboard Flash memory
UNAVCO Autonomous Continuous GPS Station		Power Demand: 5W continuous year-round Rechargeable Battery: 600-2200 Ah Deka gel cells Non-Rechargeable Battery Optional 2000 Ah Tadiran lithium ion primary batteries for winter backup. Solar panels: 160 W Sharp NE80-EJEA Wind Turbines: Two Forgen 500 LT side-mount (high wind speed, low power), or one Rutland 910-3 (moderate wind speed, medium power), or one Aerogen4 (low wind speed, medium power)	Iridium Dial-Up: Beam Communications RST-600 or NAL Research A3LA-X Iridium RUDICS: Xeos Technologies XI-100 Point-to-Point: Freewave / Intuicom 900 MHz, ethernet or serial	Onboard flash memory
IRIS/PASSCAL Autonomous Seismic Station		Power Demand: 2W continuous year-round. Rechargeable Battery: 1000 Ah Concorde AGM Primary Battery. Optional 2000 Ah Tadiran lithium ion primary batteries for winter backup 160-240 watts Sharp NE80-EJEA	Iridium SBD and RUDICS: Xeos Technologies XI-100 Point-to-Point: Freewave / Intuicom 900 MHz, ethernet or serial	Onboard Solid State Disk and USB sticks 16 GB

all of Antarctica and Greenland. Power levels are small (because of low data rates) - in the sub-watt range.

3.2 Current Capabilities

Over the past several decades, a number of research groups and consortia have developed autonomous observatories. As early as the late 1960s, an experimental Unmanned Geophysical Observatory (UGO) was field tested. Widely deployed Automatic Weather Stations (AWS) were developed at the University of Wisconsin in the 1980s. In the 1990s, both the U.S. NSF and British Antarctic Survey (BAS) funded programs to develop and instrument Automatic Geophysical Observatory (AGO) platforms to study the Earth's space environment, as well as other autonomous instruments to monitor and study seismicity and to measure geodetic motions with GPS. Recent efforts to build smaller, low-power, instrument platforms have enabled the deployment of more dense measurement arrays.

Recent NSF-supported focused and sustained engineering development exploiting new commercially available technologies has significantly advanced capabilities and future promise for low-maintenance autonomous data collection in polar regions. These efforts have yielded low power autonomous instrumentation systems that are lightweight, mechanically and thermally robust, quick to deploy, and deliver reliable year-round recording and communications. Such stations have been deployed in increasing numbers across the Arctic and Antarctic, delivering high quality datasets from geodetic GPS, broadband seismic, meteorological, and photographic instruments, with ozone and laser thermometry instrumentation to be deployed in 2011-12. To date, overall data return has averaged 80-90% for these new systems. These current-generation systems are modular, and typically accommodate instruments of up to ~5 W power consumption. By employing renewable solar and wind power sources, weights of year-round systems range from 500 lbs for a 0.5W system to 1500 lbs for a 5W system. For polar winter-spanning deployments of up to several years, weight can be further reduced by employing high energy density (lithium ion) non-rechargeable batteries. For example, 300 lb seismic systems using lithium cells have been deployed which provide ~2 W of continuous power for 2 years. If conditions allow, wind turbines can also be used to reduce the battery weight requirements for stations.

Data retrieval from remote sites is achieved using satellite communications. State-of-health data and small scientific data files can currently be robustly retrieved by ARGOS and Iridium SBD. Larger data files of up to ~20 MB/day can be retrieved using single channel Iridium dial-up technology, and slightly higher data rates and lower service (SIM card) costs can be achieved with the Iridium Router-Based Unrestricted Digital Interworking Connectivity Solution (RUDICS) direct-to-Internet service. Higher data rates have been achieved with multi-channel Iridium systems, but require greater system complexity and power consumption. Point-to-point radio (e.g., spread spectrum) links can be used in the vicinity of research stations, such as the McMurdo Sound region. System assemblies have been optimized to allow complete installation in a few hours or less of ground time with a single light aircraft flight by a small field team, including PI science groups who have received advance training. Station designs have also been tailored in power systems and insulation characteristics to prevailing conditions at specific locations, ranging from the Antarctic polar plateau with deep cold and light winds to the Antarctic and Greenland margins with moderate cold, liquid water, and extreme winds. They have been successfully installed on rock as well as snow surfaces ranging from accumulation to ablation zones.

3.3 Common Challenges and Operational Requirements

Observational platform, deployment/logistical, data delivery, and power supply considerations for scientific instrumentation in polar regions share a number of common challenges that can be traced to three key environmental aspects of polar research: extreme cold, winter darkness, and extreme remoteness. Instrumentation packages that are to operate successfully in these regions must take exceptional measures to account for these circumstances. Challenges can be grouped into two broad categories: logistical (and therefore indirectly, financial) and technical. As discussed elsewhere, instrumentation design must carefully consider minimizing size, weight, and ease of deployment while maximizing capabilities, all at suitable cost.

3.3.1 Polar Environmental Considerations. Polar environments are of course especially notable for extremely low temperatures. The Antarctic environment, in particular, is the harshest in the world. With average temperatures that range from -15°C (-5°F) in the austral summer to -70°C (-94°F) in the winter and winds that average from 20 km/h on the polar plateau to the katabatic winds in excess of 250 km/h on the coast, designing remote observatories that can operate anywhere on the continent is a substantial challenge.

Low temperatures pose significant issues for both the people installing the systems as well as the instrumentation itself. Low temperatures are a concern for any mechanical systems or mov-

Table 2. Properties of various battery technologies appropriate for remote stations

CHEMISTRY	TYPE	ENERGY DENSITY Wh/kg	CYCLE LIFE	CHARGE TOLERENCE	% SELF DISCHARGE 20C	OPERATING TEMPS, C	HAZARD	COST, USD per W-hr	OTHER APPLICATIONS
Lead Acid	Rechargeable	30-50	200-300	high	5	-40 to 60	low	.15	remote/auto
NiCd	Rechargeable	45-80	1500	moderate	20	-40 to 60	low	.75	consumer elec./Evs
NiMH	Rechargeable	60-120	300 -500	low	30	-20 to 60	low	.25	Electric Vehicles
Li-ion	Rechargeable	110-160	500-1000	very low	10	-20 to 60	high	.74	Electric vehicles
Li-ion polymer	Rechargeable	100-200	300-500	low	10	0 to 60	high	.70	consumer elec.
Li -Sulfer	Rechargeable	350-600	40-50	moderate	15	-20 to 45	medium	?	UAVs
Li/SOCl2	Primary	800	1	NA	--	-55 to 85	high	3.42	remote stations

ing parts on site (in particular, for some scientific instruments such as seismometers that depend on bearings, but also for power generation systems; see below). Low temperatures are also an issue for electronics, which contain components and systems that are generally only rated by manufacturers to -20°C for less inexpensive consumer grade items and -40°C for often difficult to source and more expensive industrial grade components. Because so many systems installed in polar regions evolve from systems originally designed for lower latitudes, temperature robustness may be very challenging. Finally, low temperatures have a number of ancillary effects that have to be accounted for. In particular typical cables and other pliable components can become unacceptably stiff or brittle, metal fatigue is more pronounced, and ultraviolet damage to plastics is more severe. To ameliorate these effects, instruments, power and communication systems, packaging, and deployment strategies must be specially tuned to the expected conditions, and off the shelf options may not be available. Such custom systems do not have the advantages of economies of scale or of extensive consumer testing and debugging.

3.3.2 Power. Solar and wind are the two most common technologies for providing power at remote autonomous sites, followed by a variety of experimental methods such as fuel cells and thermo-electric generators. High-latitude polar regions have an abundance of solar power in the summer time and none in the winter. There is abundant wind at some sites and during some seasons, and very little wind at others. Wind and solar power availability must be balanced against scientific instrumentation needs that dictate year-round power delivery. As a consequence, instrument packages universally depend on batteries to provide power during lean times.

While solar panels almost always work well in the polar summer, groups have reported various levels of success with the use of wind generators, at least for generators that would be considered "small", having outputs from several to hundreds of W (up to perhaps 1 kW). There is a clear continued need for a consolidation of information on the performance of the generators, including their usefulness in various regions, and redundant arrays of smaller wind generators may offer robustness that is lacking in single large units. For applications on the polar plateau, where winds are generally moderate, wind generators must be efficient at low speeds; on the other hand, wind generators near coastal regions (i.e., in the vicinity of katabatic winds) must withstand severe winds. The disparate levels of success imply that this particular topic needs continued and community-wide concentrated efforts to identify which aspects of wind generators lead to success and which do not, and to address the best strategies for managing this promising but fickle power source.

If an experiment is short-lived, primary (non-rechargeable) battery systems can be used and are extremely reliable. For longer deployments, rechargeable batteries are necessary. Rechargable battery systems are time-varying and nonlinear, and their capabilities must be matched to the power consumption and charging characteristics onsite, to the science and logistical budgets of the experiment. As an example, sealed lead-acid (typically Absorbed Glass Mat (AGM)) batteries are inexpensive to purchase, but because of their high mass to energy-density ratio, expensive to transport. Alternatively, lithium batteries are presently much more expensive to purchase but have a more moderate transportation cost. Because logistics budgets are often separated from scientific equipment budgets in the proposal and planning process, it is presently difficult to optimize the tradeoff between expensive logistics and expensive batteries.

Note that environmental considerations affect the power production: snowfall can quickly bury solar panels in some areas with high accumulation rates; riming on wind generators can prevent them operating, and low temperatures can make the bearings seize. Batteries (of almost any chemistry) are less efficient at low temperatures. Any power system with a water vapor exhaust (fuel cells, thermoelectric generators, internal combustion generators) must prevent the exhaust system from clogging with ice. Many sites feature usable wind at times, but also encounter sporadic extreme storm conditions that make wind a major contributor to power system and other station damage.

FIGURE 8. Installation of a low power magnetometer system at the South Pole station for testing. Stations such as South Pole serve as important testbeds where autonomous equipment can be debugged prior to deployment in remote locations.

3.3.3 Communications. For deployments that last more than a few months, a fundamental divide must be addressed: whether to telemeter data to the home institution or to retain it onsite for eventual manual recovery. This decision must be made based on scientific considerations (what is the acceptable latency for these data?), on data volume considerations (is it possible to telemeter the full volume?), and on logistics considerations.

The lifetime cost of an installation can be heavily weighted by the cost of transport to the site if multiple trips must be made to download data and assess station health, and C-130, Twin Otter, helicopter, or ship time costs can dominate the total cost of a project. Communications systems are presently limited at the poles, with Argos being the primary low-bandwidth satellite communications channel and Iridium being the primary medium bandwidth system. There is very limited visibility of the higher-bandwidth communication satellites that are available at lower latitudes. In a very few high-use areas (e.g., McMurdo Sound/Dry Valleys), it may be technically feasible to develop a broad-use and broadband ground-based communications system.

In situations where the data and state-of-health information can be telemetered, site visit costs are reduced at the expense of data communications costs. Reliable communication systems can further assist in diagnosing station problems in advance of a site visit, in re-programming and re-tasking instruments, in retrieving special data sets after notable events, and allowing for a seamless interface between global networks (which are largely real time) and polar stations.

An additional mode of data recovery would be to use a UAV that can fly itself to remote sites, circle over the observatory and retrieve data using a wireless connection, and store that data onboard for return to a manned site. Such ideas warrant serious consideration and evaluation.

3.3.4 Logistics. Addressing key Earth, ocean, atmosphere, and space science questions of the next decade will require new levels of autonomous ground-based instrumentation in Antarctica, Greenland and elsewhere in the polar regions. There are a limited number of ways to carry out such deployments, namely via aircraft, ship, and land/snow traverses. In all cases, there is a premium on small, lightweight, and easily deployable instrumentation systems. In addition, such deployments will have to be done by as small a crew (with a minimal level of highly specialized expertise) as possible. Typically, deep field air deployments are achieved with LC-130, Twin Otter, Basler, or rotor aircraft. Which aircraft is used on any particular deployment depends on the physical size of the package and its associated hardware (e.g., towers), as well as the logistical aspects of the aircraft and its operation.

All of these requirements point towards specialized, standardized packaging, power, and battery systems. Continued investments are needed to encourage

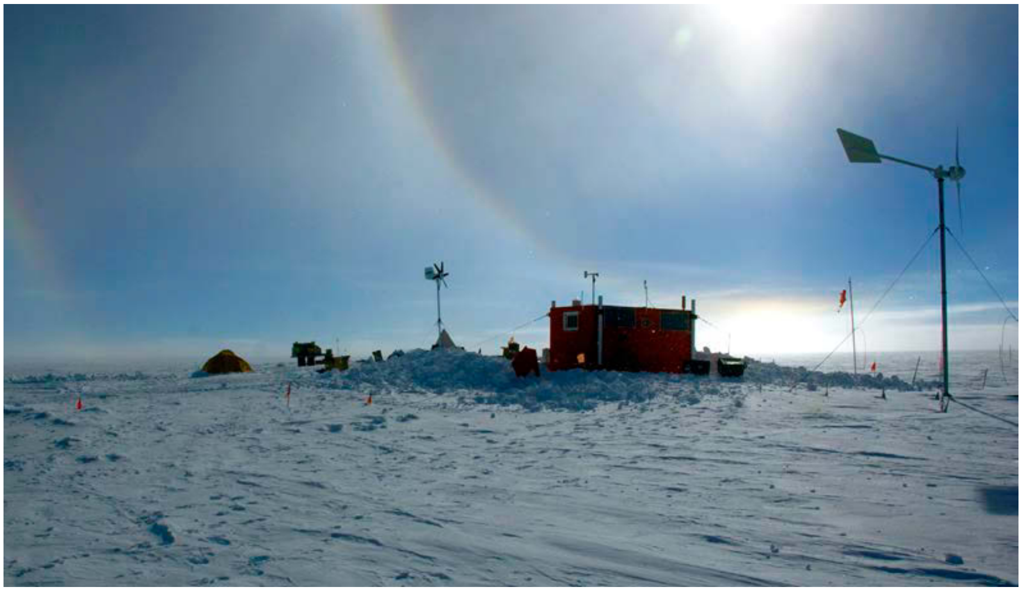


FIGURE 9. An Autonomous Geophysical Observatory (AGO) on the Antarctic Ice Sheet. Original AGO sites were powered by propane-driven thermo-electric generators with the fuel delivered to the site via LC-130 each Antarctic summer. A byproduct of power generation was a large amount of heat, which was applied to maintain the operating temperature of the electronics. Although much useful data were gathered with these stations, the high cost of the fuel airlift necessitated the development of a different type of power supply. Current power systems have been redesigned to operate on wind and solar power, and Iridium modems have been installed for real-time data transfer, leading to dramatic improvements in performance. Although the AGOs were originally intended as space physics platforms (optical and radio wave auroral imagers, magnetometers, and narrow and wide band radio receivers), the reliability and flexibility of the design has enabled other disciplines to leverage the infrastructure for new scientific instruments including seismometers, GPS scintillation receivers, and comprehensive weather stations.

steady improvements in these capabilities and to optimize logistical and science support resources, while diverse U.S. science consortia and communities and international partners must cooperate and coordinate efficiently to recognize commonalities and opportunities for scientific and logistical partnerships.

3.3.5 Human resources. The success of polar instrument deployments depends at least as much on the skills of the people developing, preparing, and deploying the instruments as it does on the underlying technology. The human element will never be completely replaced in our work. Because of the special demands and remoteness of polar deployments, novice personnel must be trained by experienced personnel, including training in the field, to be successful. This requires continued investment in technical human resource development for the consortia, academic departments, contractors, and others that carry out polar science fieldwork.

3.3.6 Testing facilities/testing cycle. Some system integration issues can be tested a low latitudes, and so a readily accessible mockup system is essential for initial testing of new system components, particularly for more complicated “supersites”. For example, the AGO project maintains a “clone” facility for testing in North America. Realistic field conditions are difficult to replicate at low latitudes. This suggests the need for a centralized, realistic proving site that, as much as possible, has year-round access. A suitably supported facility at South Pole and/or McMurdo Station is a possible option for developing a suitable U.S. testing facility that can as much as possible speed up the testing cycle for new generations of instrumentation systems. UNAVCO and IRIS/PASSCAL have reaped good rewards from their McMurdo Observation Hill and South Pole test sites since 2005, including demonstrating new hardware and systems integration, and collecting rapid feedback when problems are encountered. Greenland and Alaska also provide good options for testing facilities, and offer easier access from the United States.

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While significant progress has been made in designing and operating autonomous polar observing systems in the past decade, current systems still fall short of meeting cost, weight, and technical requirements posed by the science of the next decade. To meet these challenges, we must build on the considerable experience collected by previous and ongoing efforts, while continuing to harness improvements and new technologies. Finally, we need to further engage and sustain a broad community of science and technical partners who will contribute to and utilize the results of these efforts. Overall, system integration should remain a priority. Continued technical cooperation and information sharing between facilities, support contractors, science groups, and funding agencies, will optimize usage of NSF-OPP resources.

In many cases, the nature of geophysical research is such that further scientific advances require increasingly detailed observations, whether in the form of higher temporal/spatial resolution or with the use of new instruments. For remote measurements, this means an increased need for reliable (perhaps modular or scalable) observatories, likely with increased power and bandwidth capabilities. It remains very important to seek not just incremental advances in these technologies, but developments that might provide order of magnitude improvements in existing capabilities.

In the sections that follow, a review of some current technological developments is first presented to provide examples of the type of work that is currently being carried out. This is by no means an exhaustive list of such developments. Some possible deployment strategy suggestions are below, including a discussion of how groups might exchange information. Finally, we describe various strategies that can be used to support future advancements.

4.1 Development in Progress. An advanced Iridium device has recently been developed that allows maximized throughput using Iridium technology, can operate at low temperatures and has lower power consumption than previous devices. Reliable operation to -50°C, data rates of up to 10MB/day, and connectivity to generic IP-based devices have been demonstrated. Development is continuing with prototype seismographic and GPS deployments in Greenland and in Antarctica. Both the IRIS/PASSCAL and UNAVCO facilities have shared the RUDICS development with a resultant system that uses standard internet protocols to work with any "internet appliance". The ability to retrieve higher data volumes from a low-power device will dramatically improve the efficiency and decrease the latencies of seismic event and structure, GPS-based ionospheric and glacial, and other higher-data-rate studies. It is also anticipated that the planned deployment (2015-2017) of the higher data rate Iridium NEXT constellation and IP-based communications system is expected to further increase efficiency and data yield of science projects funded throughout NSF-OPP. This emerging technology will need to be be monitored, tested, and strategically employed when it comes online. The NSF-Iridium-DOD arrangement for Iridium airtime must be maintained in coming years for this to remain economically viable for the scientific community. A next-generation UW-Madison AWS instrument is presently under development that will integrate with a polar GPS or seismic station using a single power and communications link. A prototype will be deployed with UNAVCO at the McMurdo testbed in Antarctica during the 2011-12 austral summer, as proof of concept for adding AWS instrumentation to POLENET stations. In combination with the Iridium RUDICS+SBD communication technology, this instrument will deliver higher quality meteorological data in near-real time, benefiting meteorological research and forecasting as well as aircraft logistics, and will offer the possibility of additional integrated sensors in future years. An integrated IRIS/UNAVCO developed polar GPS/seismic station has also been demonstrated that uses a single power system and point-to-point communications link. Further Iridium RUDICS development should allow multiple generic IP-based instruments in packages of this type to utilize a single Iridium modem. Non-rechargeable lithium batteries are a proven asset to greatly reduce system weight for intermediate-term (1-2 year) deployments. Due to ongoing advances in lithium battery chemistries, a similar lightweight power system employing rechargeable batteries now appears feasible, and efforts are currently underway at IRIS/PASSCAL to develop appropriate incremental battery and charging systems for these types of batteries.

Low-power (several Watts) vertical-axis wind turbines have proven their ability to greatly reduce battery requirements in year-round operation of power systems. Although technological advances have increased reliability, performance and reliability are not yet sufficient to guarantee sustained wintertime power production at the most volatile wind locations. However, several manufacturers are now offering new and promising vertical axis turbines that UNAVCO will be testing in the Antarctic in 2012. Medium-power horizontal-axis turbines have been deployed with excellent success in low-wind, extreme cold environments (e.g., the Antarctic polar plateau and interior Greenland). Similar turbines also hold great promise to sustain future higher-power sites (10-20 W) in moderate to extreme wind environments, while still minimizing system weight. Current testing is in progress at the UNAVCO McMurdo station GPS test-site, and a field project deployment is planned for the 2011-12 austral summer. Successful operation of multiple instruments with lead-acid batteries is often routine in the coastal areas of the Arctic and Antarctic with simple enclosures and minimal thermal insulation. For operation in the coldest regions of the high Antarctic Plateau, or when using more cold-sensitive instrumentation, outstanding thermal performance has been repeatedly demonstrated by using advanced vacuum-insulated panel enclosures. More development is needed to bring the manufacture of these enclosures from the laboratory to a more easily mass produced product.

4.2 Deployment Strategies. While each discipline has specific discipline-driven measurement requirements that motivate sensor deployment strategies, there are strategic models that can benefit some or all investigators seeking remote polar measurements.

4.2.1 Integrated Super-Sites. By identifying and collating scientific goals and associated geographic targets, it may be possible to identify certain "super-sites" where logistics economy could be achieved through the installation of multiple and/or master autonomous system sites that could be operated by multiple investigators across multiple disciplines. The Autonomous Geophysical Observatory (AGO) systems deployed by the space sciences community are an example of this strategy. These systems provide the power, data acquisition and telemetry infrastructure to support multiple instruments/sensors. Indeed, for some AGO installations, while supporting a variety of space science remote sensing instruments, they have recently started to also provide support for other disciplines including the seismic and remote weather communities.

4.2.2 Multi-Autonomous Super-Sites. In some cases, individual disciplines have well developed and engineered systems with power and communication solutions. In this case, integration with other disciplines and sensors may require considerable additional engineering and could actually reduce reliability. Since the major reason for co-locating instrumentation is the enormous cost and difficulty of transport to the site for installation and maintenance, it is still efficient to co-locate sensors, even if each sensor relies on independent power and communication systems. Technicians from the different disciplines can be cross-trained to service a variety of instrumentation at a useful level to facilitate cross-disciplinary maintenance of such sites. The recent co-location of GPS and seismic sensors at POLENET sites is an example of this strategy.

4.2.3 Shared Logistics. Cooperation between disciplines is essential even in the case where each discipline has strict siting requirements that prohibit close co-location. Autonomous instrumentation within a given region may require a cooperative base camp, with sites serviced by Twin Otter using a hub-and-spoke strategy. With potentially increasing use of traverses, it may be possible in the future for multidisciplinary instrumentation to be emplaced and/or serviced along a traverse path, sharing the traverse logistics in much the same way that ships are routinely shared in Ocean Sciences.

4.3 Framework for Knowledge Exchange and Continued Progress

Principal goals of the APOS workshop were to identify technical and logistical needs in the polar regions, and to scope strategies for ongoing knowledge exchange and advancement of capabilities and exploitation of efficiencies. These efforts should ultimately expand knowledge and capabilities both within and across geoscience disciplines. It was universally agreed that there is a need to continue and expand communication, and that the opportunities afforded by open, efficient, and collaborative knowledge exchange are essential to maximizing data return per dollar spent. However, it is also clear that facilitating and sustaining such knowledge exchange is a challenge that will require continued leadership from funding agencies and the science communities involved. Establishing and supporting a framework or infrastructure for sustained knowledge exchange on technical issues and logistics coordination should be a priority for the polar geoscience community.

4.3.1 Needs and opportunities for exchange of technical knowledge. In the most general sense, stationary autonomous polar observing systems are composed of a sensor system (including the measuring instrument and a data acquisition system), a power system, a communications system (with varying levels of remote accessibility), and an enclosure system. The primary need for technical interchange about these subsystems is to take advantage of lessons learned by other users, to establish and apply best practices for overall system design and to provide a baseline and infrastructure to facilitate future innovation. In addition to exchanging information about successful designs and outcomes, it is desirable to document approaches that proved unsuccessful (what some might call a "fail log"), to prevent unnecessary repeat failures.

Sensor and deployment strategies will tend to be more discipline-specific than power/communications/enclosure systems, and the cutting-edge technical issues in each realm may also be relatively discipline specific. However, exchange of knowledge gained must be cross disciplinary — indeed, well-documented best practices may be of most use to novice and 'out-of-discipline' users of a particular measuring device — and the greatest utility will be achieved if intra- and inter-disciplinary communication channels are open during the development process.

4.3.2 Needs and opportunities for exchange of logistical knowledge. Logistics knowledge consists essentially of knowledge of who is (or was, or will be) where, when, doing what, and with what resources. The most obvious opportunity presented by effective exchange of such information is that of potential cost reduction for the remote operations needed to install, service, and remove autonomous systems. Prior to deployment, knowledge of prior and existing nearby observational or operational efforts can lead to more efficient planning, and to system optimization for local conditions, as well as to opportunities for shared logistical arrangements and potentially reduced total expenditures on equipment and personnel transport. Colocation of multiple observing systems in one of the modes described above can then be planned , if appropriate, provided that all relevant parties are aware of the opportunity. After deployment, shared knowledge of logistics needs can lead to opportunities to coordinate service visits, or take advantage in a 'target of opportunity' fashion of the presence of logistics support and personnel operating near an observatory needing servicing, rather than planning separate service visits. Similar opportunities pertain at demobilization.

One challenge in coordinating observatory siting and logistics is simply obtaining comprehensive knowledge of what observatories are currently, or have recently been, on the ground, and of who is likely to be where, and when. Because essentially all US Antarctic scientific activity is coordinated through the NSF Antarctic logistics provider, and much Arctic activity is coordinated through the NSF Arctic logistics provider, a key database of such information for active and recent projects exists. Currently, some of the information is easily discoverable, and some is not. An additional challenge stems from the timescales of logistics planning and funding decisions: multiple projects can only be coordinated with any certainty once funding has been approved for all of them, and they may be at different stages of planning when logistics decisions have to be made. Finally, researchers are likely to be more aware of collaborative field activities in their own fields than in other disciplines. For 'target of opportunity' service visits, additional knowledge is required: the need for a visit (i.e., a problem) must have been identified, and it must be coordinated with available personnel and existing logistics plans in a way that is manageable by the field party.

4.3.3 Approaches for sustained exchange of technical knowledge. Technical knowledge needs to be exchanged between different investigator groups, between different facility technical and engineering groups, between investigators and facilities, and with the commercial sector. Several strategies for the ongoing, sustained exchange of technical knowledge were identified at the APOS workshop, along with successful examples of each that could be expanded. These fall into several categories:

(1) Web-based, easily discoverable documentation of best practices, successes, and failures. Websites can effectively document successful approaches and best practices, providing an important head start for anyone wishing to deploy autonomous polar observing systems. They also help investigators to know what resources and expertise are available from the facilities and elsewhere. Such easily discoverable documentation of technical approaches should be considered an essential part of development and PI-support activities. A useful expansion of this type of documentation would be to include information on technical approaches that have been attempted but failed, are obsolete, or are otherwise not recommended. The IRIS/PASSCAL and UNAVCO community facilities currently support documentation websites covering recommended power, communications, and enclosure components, as well as design drawings and other materials. The website PolarPower.org was funded by the National Science Foundation with the goal of providing a useful working resource for researchers in choosing, designing, implementing, and maintaining remote power systems in polar environments. Improving cross linkages between these and other sites is desirable. In addition, providing a simple forum for individual investigator groups to share information on their experiences would be useful. A moderated or monitored wiki page or Google group might be an effective approach. A challenge is to maintain documentation sites like these so that they remain current and continue to incorporate new knowledge. Identifying one or several sites as key repositories, with clear responsibility for maintenance, would help to address this challenge.

(2) Cross-disciplinary technical working groups, facilitating communication between engineers and PIs in different polar-science disciplines. A successful example is the group of polar engineers at IRIS/PASSCAL and UNAVCO who worked jointly to develop power/communication/enclosure systems under two NSF Major Research Instrumentation efforts with the assistance of a Polar Networks Science Committee whose members are drawn from both consortia communities and staff. One challenge in exchanging technical knowledge is that existing forums for such exchange (e.g., informal exchange at scientific meetings) tend to be relatively discipline focused and difficult to sustain. However, it is clear that communities and NSF can broadly benefit from increased exchange across disciplinary boundaries. An organized, semi-formal or formal technical interchange group with participation from engineering and technical experts from a range of disciplines could be of great value in supporting such an ongoing, sustained exchange of information. Such a group could exchange information

electronically, but should meet occasionally in person as well, perhaps coordinated with other meetings. This Polar Data Technologies group, in addition to serving as a router for new information into separate scientific communities, might also provide valuable inputs for the best-practices (and failures) and maintain the documentation described above.

(3) Conferences with a polar-technology focus, where technical advances and plans can be shared with a wide, cross-disciplinary audience; an example is the SRI International Polar Technology Conference (http://polartechnologyconference.org/) that has been held annually for several years, sometimes co-hosted by one or more of the community instrumentation and facilities consortia. These conferences have proven successful in promoting information exchange between support facilities/logistics providers (e.g., SRI, UNAVCO, IRIS), key vendors (e.g., Iridium), and a widening sphere of polar investigators. The focus is on technical challenges, advances, and near-term plans for development activities. Maintaining and enhancing the Polar Technology Conference series, or similar regular events, would help support necessary community building and the general exchange of knowledge about both best practices and nascent development efforts.

(4) Internships at the NSF supported polar research groups and facilities provide opportunities for students to gain broad experience in polar science, determine if they have an interest in a particular career, and create a network of contacts. Internships provide facilities with inexpensive and highly motivated labor. International polar research organizations may also offer internships bringing new perspectives and fostering international cooperation.

All of the above mechanisms for the exchange of technical knowledge would benefit from enhanced international participation. Such participation should be explicitly welcomed and invited, and an effort should be made in each case to engage key international individuals, funding and support agencies, and scientific institutions (e.g., SCAR).

4.4 Strategies for Future Development & Implementation

The results of this workshop make it clear that great scientific advances are possible in the next decade using data from autonomous polar observing systems, and that increased coordination between groups can produce broad science benefits. Likely technical advances in power and communications will make it possible to obtain observations at higher density and covering a larger region than previously possible, and in more cost-effective ways. A key question remains how to best organize the communities in order to achieve the maximum return for the investment of research dollars. There is clearly a role for several types of organizations in the development of next generation observing systems.

4.4.1 Investigator-led technical teams. The initial development and deployment of observing equipment has traditionally been carried out by small groups of scientists, technicians, and graduate students, organized by one or more PIs at academic and/or research institutions. This type of organization is usually essential for producing an initial peer-reviewed proof-of-concept, since the lead scientist has a vision for how new observations can move the science forward.

Under this model, the PI, along with key technical experts, designs and deploys the equipment with funding from NSF-OPP MRI and or research grants. The advantage of this approach is the close coupling between science objectives and technical development effort. Effort is tightly focused on objectives that relate directly to solving science problems that are selected by the lead scientist and approved by peer review. Such teams also readily involve graduate students, thus educating the next generation of scientists on the interfaces between technical innovation and scientific discovery.

The disadvantage of this model is that such a team is nearly always very small, so that one technician often carries the entire knowledge base of the development effort, detailed documentation may not exist to the extent that another team could replicate the effort, and the departure of this key person may be very difficult or impossible for the institution to overcome. Because of these issues, the continuity of such teams can be difficult to maintain, given that they are typically supported by NSF grants of 2-4 years duration, with each one subject to the changing priorities and decisions of peer-review panels. It can also be difficult for very small teams with tight focus to remain innovative and familiar with the latest technical developments, and recent budget and personnel cuts at many universities and government agencies have made the long-term maintenance of in-house technical expertise more difficult. Nonetheless, it is clear that there will always be a critical role for investigator-led technical teams, particularly regarding unique development efforts and novel creative ideas.

A way forward to improve the performance of this model might be to piggyback future innovative instrument development on the common infrastructure for autonomous polar stations that is currently provided by the Disciplinary Facilities. The PI–led technical instrument teams create the payloads that are supported by the basic mechanical, thermal, power, and communication elements of the highly supportable and successful autonomous stations now being deployed. This method will still require a thorough integration effort but will not duplicate what the NSF OPP already supports. Several PI-led projects are already utilizing this model to deploy meteorological, thermometry, and ozone instruments on a Facility-provided platform.

4.4.2 Disciplinary consortia and facilities. Several fields, noting recurring and evolving peer-reviewed demands for equipment, new development, and technical support, have successfully established consortia facilities. Well-recognized examples operating in polar regions include the UNAVCO facility for geodetic support and the IRIS consortium IRIS/PASSCAL facility for seismology. These facilities maintain much larger pools of community-use instrumentation than could be maintained by individual investigators. Such facilities are commonly funded by NSF Instrumentation and Facilities programs at NSF, with additional funding from OPP and other government agencies, and are governed by consortia boards and committees selected from the user community. UNAVCO and IRIS support a broader scientific community beyond the polar regions, and their polar efforts are a subset of larger operations, requiring specialized staff and equipment for polar operations.

An advantage of facilities is that they can commonly support longer-lived technical development efforts with larger numbers of technical staff than academic departments. This facilitates greater continuity and specialization in polar support. Community governance and a continually changing set of user community demands dictated by successful peer reviewed proposals further requires that successful facilities maintain a high level of responsiveness and service to science teams. Facilities are also typically well integrated with data management and distribution facilities, helping to ensure the proper archival and redistribution of data and metadata at community-governed data facilities.

A disadvantage of large facilities can be a less direct connection with highly specific scientific objectives. The facility governance structure, which includes several layers of committees populated by scientists, as well as feedback from NSF and peer facility review, must respond to optimize priorities for development efforts while serving a large and diverse population of upcoming and ongoing projects. This can lead to competing pressures, such as whether to support current scientific projects or undertake new development efforts. The facility model thus works best when demands for large numbers of versatile but standardized instruments from a large community, rather than small numbers of highly specialized ones from a small community, are strong science drivers.

To further explore the future role of facilities, the NSF OPP Antarctic Earth Science program has funded a Polar Facilities Planning Meeting, to be held in Arlington VA on September 8-9, 2011. The goal of this workshop is to better develop and systematize relationships between NSF, the polar community, and the UNAVCO and IRIS/PASSCAL facilities.

4.4.3 Coordinating organizations. Investigators and disciplinary-based facilities constitute an essential component to facilitate better coordination between diverse polar research communities to help ensure that technical development efforts advance to meet the ambitions of the research community for the best science, are not duplicated across multiple groups, and that logistics costs are minimized. However, success will naturally require further leadership and partnership efforts from other organizations.

Ultimately NSF, as the funding agency, is tasked with ensuring that funds are well programmed and that logistical plans are coordinated. Indeed, NSF program managers seek to avoid duplication of effort in technical development awards, and some logistical coordination currently occurs through field season planning conducted by the Antarctic and Arctic logistics providers. However, these avenues may not readily incorporate international efforts and may currently lack the deeper level of coordination that is essential for to optimize the deployment and operation of polar observing systems.

South Polar or North Polar international coordination committees may also help. For example, the SCAR (Scientific Committee on Antarctic Research) organization is one possible forum for coordination. However, SCAR committees are usually not well funded and do not meet frequently enough to integrate well with the US science review structure.

The Polar Technology Conference, which is held annually at different sites around the US, is an evolving and important organization and meeting for coordinating technical development activities and disseminating the results of recent efforts. This meeting fills a valuable niche for coordinating key technical developments, but does not address the relationship between technical development and science goals, or logistical issues.

5 Conclusions and Recommendations

The high latitudes are critically important regions of scientific study that are difficult to access and expensive to instrument. Recent advances in autonomous sensors, power systems, communications technology, and deployment techniques have allowed researchers to access locations and times of the year that were impossible even a few years ago. However, in the years ahead more deployments will be necessary to answer the critically important scientific questions affecting people across the globe. To that end, we suggest the following steps to solidify the recent gains:

1. Autonomous polar deployments should be undertaken as cooperative ventures between multiple communities and with international collaboration, if possible.

   a. The establishment of super-sites where many disciplines install instruments at the same geographic location and share the logistical costs of the deployment.
   b. Much-improved communication between disciplines and between countries on planned field camps, traverses, cruises, and areas of special focus.
   c. A comprehensive database of existing and in-progress autonomous deployments. The best solution would be a recognized website that is professionally maintained and regularly updated.
   d. Continued exchange of knowledge, successes and failures, advancements, and opportunities through the Polar Technology Conference and by working closely with instrumentation consortia such as UNAVCO and IRIS/PASSCAL.

2. Autonomous polar technology development must be encouraged and supported at various levels.

   a. Individual PI-led efforts are often innovative, targeted, and high-risk...but also high-reward. Under the right circumstances these efforts have an important role and must be continued. Knowledge gained from such teams should be incorporated into the information systems that may be maintained by instrumentation consortia.
   b. Physical deployment issues such as logistics, packaging, deployment strategies, etc, must be shared and continually improved as experience is gained. The instrumentation consortia should be charged with maintaining and disseminating this knowledge.
   c. Power systems must be improved with an eye to ongoing battery technology advances. The initial cost burden of advanced-technology batteries must be weighed against the long-term logistical costs of older-technology batteries.
   d. Communications technology is evolving rapidly. There is short-term stability/stagnation, with little change in bandwidth for polar communications in the immediate future. However, we recommend aggressive investment in long-term communication technologies.
   e. Human resources are at a premium. Students should be afforded opportunities at the consortia; at institutions doing instrument development; and in the field. “Cross-training” that transcends the traditional disciplinary/technical and institutional boundaries should be strongly encouraged so that fewer people need to go to the field.

3. A management structure for autonomous polar observing systems is perhaps the most difficult question. Coordination is needed, but the need to preserve autonomy of efforts within the different research communities is also recognized, and thus the workshop does not recommend a “top-down” strategy. The research community is small, so another oversight committee would be a heavy burden on scientists’ time. We propose instead:

   a. The major stakeholders in polar observing systems should communicate through forums that already exist. Examples of multidisciplinary venues include the IRIS/UNAVCO Polar Networks Science Committee and the Scientific Committee for Antarctic Research (SCAR) Open Science Conferences.
   b. The establishment of a professionally maintained and updated website, as described above. The website will inform and bring together the community and will facilitate a degree of self-organization.
   c. The continuation and enlargement of the Polar Technology Conference (or a similarly oriented conference) to allow rapid dissemination of newly developed technologies.

6.1 Workshop committees:

WORKSHOP ORGANIZING COMMITTEE

Douglas Wiens (chair)	Seismology	Washington University in St. Louis
Robert Clauer	Space Physics	Virginia Tech
Matthew Lazzara	Meteorology	University of Wisconsin
Meredith Nettles	Seismology & Glaciology	Columbia University
Leigh Stearns	Glaciology	University of Kansas
Al Weatherwax	Space Physics	Siena College
Terry Wilson	Geology & Geodesy	Ohio State University

WORKSHOP REPORT WRITING COMMITTEE

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Rick Aster	Seismology	New Mexico Tech
Robert Clauer	Space Physics	Virginia Tech
Matthew Lazzara	Meteorology	University of Wisconsin
Marc Lessard	Space Physics	University of New Hampshire
Gordon Hamilton	Glaciology & Geodesy	University of Maine
Meredith Nettles	Seismology & Glaciology	Columbia University
Leigh Stearns	Glaciology & Geodesy	University of Kansas
Al Weatherwax	Space Physics	Siena College
Terry Wilson	Geology & Geodesy	Ohio State University

6 Appendices

6.2 List of Workshop Attendees

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6.3 Workshop Program

Thursday, Sept 30

8:30	Welcome and Introduction	Organizing Committee
8:40	NSF Context	Vladimir Papitashvili Alex Isern Martin Jeffries

- **Morning Session**

The Vision of a Polar Observing System- Disciplinary Perspectives
(each talk 25 minutes, 5 minutes for questions/discussion)

9:00	Geodesy	Mike Bevis
9:30	Seismology	Andy Nyblade
10:00	Glaciology	Slawek Tulaczyk
10:30	Coffee Break	
11:00	Space Physics	Lou Lanzerotti
11:30	Meteorology	John Cassano
12:00	Discussion	
12:30-1:30	Lunch	

- **Afternoon Session**

Current Instrumentation and Challenges Ahead
(each talk 20 minutes with 5 minutes for questions/discussion)

1:30	Geodesy –UNAVCO polar instrumentation	Bjorn Johns
1:55	British Antarctic Survey Development	Mike Rose
2:20	Seismology – IRIS polar instrumentation	Tim Parker
2:45	Space Physics – AGOs and magnetometers	Bob Melville
3:10	Coffee Break	
3:40	Meteorology Observations and Challenges	Matt Lazzara
4:05	Glaciology instrumentation #1	Alberto Behar
4:30	Glaciology instrumentation #2	Carleen Tijm-Reimer
4:55	Sea Ice Deployments	Don Perovich
5:20	Discussion	
5:40	Posters and cash bar	

Friday October 1
The Polar Observing Systems of the Future

8:30 Logistical Constraints .... Jessie Crain

9:00 Power systems/Batteries .... Seth White & Tim Parker

9:30 Communications .... Pat Smith

10:00 coffee break

10:30 Discussion – technical issues

- 11:30 Breakout Session #1

group # 1 Power Systems & Packaging - leader Al Weatherwax
group #2 Communications Systems - leader Matt Lazzara
group #3 Antarctic Siting and Logistics – leader Terry Wilson
group #4 Arctic Siting and Logistics – leader Meredith Nettles

12:30-1:30 lunch

1:30 presentation of breakout group results

- 2:00 Breakout Session #2

4 parallel groups to discuss the future, including technology, organization, siting, logistics
leaders: Doug Wiens, Leigh Stearns, Bob Clauer, Sridhar Anandakrishnan

3:00 coffee break

3:30 presentation of breakout group results

4:00 plenary – open discussion, finalize action items

5:00 adjourn

6.4 Web Resources for Autonomous Polar System Design

Wisconsin Automatic Weather Station Project	http://amrc.ssec.wisc.edu/aws/
McMurdo Long Term Ecological Research (LTER)	http://www.mcmlter.org/
IRIS/PASSCAL Polar Seismology	http://www.passcal.nmt.edu/content/polar
Greenland Ice Sheet Monitoring Network	http://glisn.info/
UNAVCO Polar Geodetic Support	http://www.unavco.org/polartechnology
Polar Technology Conference	http://www.polartechnologyconference.org/
Power Systems for Polar Environments	http://www.polarpower.org/
Antarctic Space Sciences (AGO & Penguin projects)	http://Antarcticspacescience.org
POLENET project site	http://www.polenet.org/
Augsburg College Space Physics	http://space.augsburg.edu/index.html
British Antarctic Survey Instrumentation	http://www.antarctica.ac.uk/bas_research/instruments/index.php
Arctic Research Mapping Application	http://armap.org

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