IRIS

Proposal To NSF For Support Of

SEISMOLOGICAL FACILITIES FOR THE ADVANCEMENT OF GEOSCIENCE AND EARTHSCOPE

October 1, 2013– September 30, 2018

VOLUME 1:

Project Description and Scientific Justification

The cover of *Seismological Facilities for the Advancement of Geoscience and EarthScope* depicts some of the major resources provided by IRIS to support research and monitoring in seismology. The US map at the top shows the location of more than 1600 sites where USArray Transportable Array stations have been installed in the conterminous United States and 290 sites for proposed installation in Alaska. The smaller white symbols in the US map show the locations of recent experiments that have used USArray Flexible Array and PASSCAL equipment (numerous earlier PASSCAL experiments in the United States are not shown). The bright circles on the global maps (both east and west hemispheres) show the locations of Global Seismographic Network stations operated by IRIS, through the University of California, San Diego, in collaboration with the USGS. Seismograms are shown flowing into and out of the IRIS Data Management Center in Seattle, WA. The background in the lower half of the cover is from a seismogram showing a continuous 40-year record (1972–2012) of global earthquakes, created from digital waveform data archived at the IRIS Data Management Center, from GSN station ANMO and its predecessor ALQ operated by the USGS in Albuquerque, NM.

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VOLUME 1:
Project Description and Scientific Justification

Submitted to the
National Science Foundation
Division of Earth Sciences

By the
Incorporated Research Institutions for Seismology
1200 New York Avenue, NW, Suite 400
Washington, DC 20005

On Behalf of the
Board of Directors and
116 Member Research Institutions
of the IRIS Consortium

September 2012

VOLUME 1: Project Description and Scientific Justification

Section I

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 11-1

NSF 11-1

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)

EAR - INSTRUMENTATION & FACILITIES

FOR NSF USE ONLY

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SHOW PREVIOUS AWARD NO. IF THIS IS
☐ A RENEWAL
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IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE

Incorporated Research Institutions for Seismology

AWARDEE ORGANIZATION CODE (IF KNOWN)

4076212000

ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE

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Incorporated Research Institutions for Seismology

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Incorporated Research Institutions for Seismology
1200 New York Avenue NW
Washington ,DC ,200056142 ,US.

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
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☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Seismological Facilities for the Advancement of Geoscience and EarthScope**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 152,382,248	60 months	10/01/13	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

☐ BEGINNING INVESTIGATOR (GPG I.G.2)
☒ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
☒ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☐ EAGER* (GPG II.D.2) ☐ RAPID** (GPG II.D.1)
☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ________
PHS Animal Welfare Assurance Number ________
☐ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number ________
Exemption Subsection ________ or IRB App. Date ________
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
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☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT

PI/PD FAX NUMBER

202-682-0633

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Project Summary

Seismological Facilities for the Advancement of Geosciences and EarthScope
Incorporated Research Institutions for Seismology
August 2012

The IRIS Consortium (Incorporated Research Institutions for Seismology) provides a suite of community-governed, multi-user facilities for instrumentation and data management to support research and education in seismology and the Earth sciences. A high-performance network of more than 150 permanent stations provides data for global studies of earthquakes and deep Earth structure. A mobile array of more than 400 seismometers and atmospheric sensors is completing a traverse of the conterminous United States and preparing for deployment in Alaska. More than 4000 portable instruments (including magnetotelluric systems) are available for short-and long-term loan to university-based researchers for detailed studies as part of NSF-funded field programs. Future observing needs are addressed via systematic engineering efforts. Data from all of these observational systems, along with extensive collections of seismic data contributed by other organizations, are freely and openly available through the IRIS Data Management Center.

Intellectual Merit

Data collected and distributed through IRIS facilities form the observational basis for most of the fundamental studies in seismology carried out by researchers at US universities and in many organizations worldwide. The stability and high quality of the permanent observatories capture both the short-term details of faulting during the seconds to minutes of rupture in major earthquakes as well as decadal-scale changes in global earthquake activity. Data from permanent, mobile, and portable arrays are used to resolve features in Earth structure over scales that range from the whole Earth, to lithosphere, to regional basins, to fault zones. Seismological observations provide fundamental information on Earth structure and processes that, in combination with other geoscience disciplines, contribute to enhanced understanding of how the active Earth evolves and deforms. As a part of EarthScope, these seismological observations contribute to multidisciplinary studies that focus on the structure and dynamics of North America and contribute to unraveling the history of deformation of the continent.

Broader Impacts

The IRIS program in Education and Public Outreach directly links the public and schools with the activities of an academic research community by demonstrating how basic seismological observations are made and used in Earth science investigations. Through a variety of activities that extend from the provision of classroom and web resources, to museum displays, public lectures, and internships, IRIS encourages students to engage in scientific inquiry and appreciate the importance of the Earth sciences in their lives.

In addition to supporting fundamental research, the seismological resources provided by IRIS serve dual use by contributing directly to societal needs through reporting of global earthquake activity and applications in monitoring nuclear test ban treaties. Scientific and technical outreach by IRIS and its members as part of their international activities also provides assistance and guidance in the development and implementation of earthquake monitoring networks and hazard assessment, especially in developing countries.

Introduction

Seismology, as a fundamental tool to monitor and understand earthquakes and probe Earth's deep interior, has never been more relevant. The major earthquakes of the last decade have devastated countries and raised global awareness of our planet's vulnerability, especially in the fragile infrastructure of the developing world. Earthquakes caused by the injection of fluids into the crust are attracting attention as new methods are being exploited for extracting hydrocarbons and sequestering carbon dioxide. The proliferation of smaller weapons in the fragmented geopolitical landscape is requiring ever greater knowledge of Earth structure to monitor potential nuclear tests. Meanwhile, basic scientific problems from Earth's atmosphere to its core require information that can be best gleaned from seismic waves. The demands on the technical resources and skills of seismologists are being expanded constantly. The *Seismological Facilities for the Advancement of Geosciences and EarthScope* proposal is designed to meet these challenges.

With this proposal, the Incorporated Research Institutions for Seismology (IRIS) responds to the January 2010 request from the National Science Foundation (NSF) to merge the management of the traditional IRIS core programs and the USArray component of EarthScope. USArray has been closely integrated with, and built on, IRIS core operations since the early planning stages for EarthScope in 1998. Merging the management of all NSF Division of Earth Sciences (EAR)-supported IRIS activities under one Cooperative Agreement presents challenging and potentially beneficial opportunities for streamlined management and synergies between programs. IRIS management and the Board of Directors have already responded to this challenge by implementing changes in the IRIS management and governance structure under the current Cooperative Agreement with NSF that began in 2010. Under the new structure, IRIS observational programs have been merged into a single Instrumentation Services Directorate, and linkages have been strengthened between these activities and parallel structures for Data Services and Education and Public Outreach. At the technical level, the IRIS experience with USArray has opened opportunities for innovation in instrumentation, field practices, and data services that will be extended under this proposal to the benefit of all components of IRIS activities. For the scientific community served by IRIS, the opportunity to review and reflect on the structure and implementation of IRIS programs has stimulated broad discussions about how the well-established resources of the IRIS core programs can be sustained and merged with lessons learned during the very successful EarthScope program, in a way that stimulates new scientific pathways and experimental modalities.

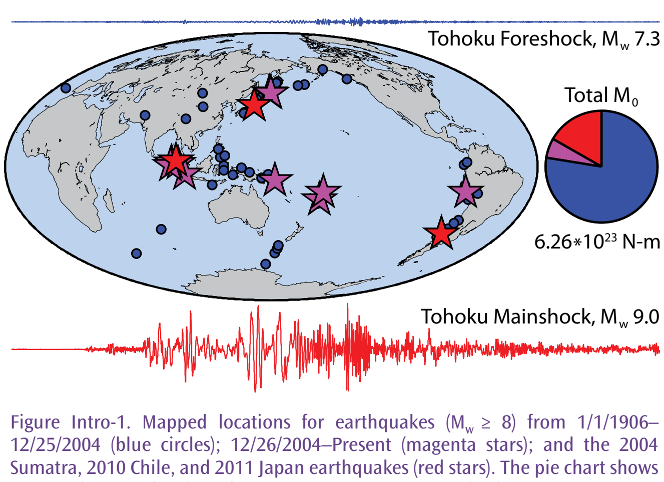


Figure Intro-1. Mapped locations for earthquakes ($M_w \geq 8$) from 1/1/1906–12/25/2004 (blue circles); 12/26/2004–Present (magenta stars); and the 2004 Sumatra, 2010 Chile, and 2011 Japan earthquakes (red stars). The pie chart shows the relative contribution of these groups to the total seismic moment released since 1906. The three largest, most recent earthquakes constitute 21% of the total moment and were all extensively recorded by IRIS broadband stations in the Global Seismographic Network and, when timing allowed, active PASSCAL deployments and the EarthScope Transportable Array stations. The two seismograms, recording two hours of north-south oriented ground motion at GSN station FURI (Ethiopia), show the difference in energy released by the M_w 7.3 Tohoku, Japan foreshock (3/9/11) and the M_w 9.0 mainshock (3/11/11). Using IRIS facilities, these events have been more fully quantified than any preceding great earthquakes in seismological history.

A series of community-led workshops and National Academies reports on scientific opportunities for seismology and the Earth sciences has informed the science goals that the integrated IRIS facilities are designed to serve. These reports include the 2010 *Seismological Grand Challenges in Understanding Earth's Dynamic Systems*, the 2011 science plan for EarthScope (*Unlocking the Secrets of the North American Continent*) and the 2012 report from the National Academy of Science's Board on Earth Sciences on *New Research Opportunities for Earth Sciences*. Various IRIS, EarthScope, and GeoPRISMS workshops, many of them directly related to planning for this proposal, have also provided opportunities for discussion of science goals and the way in which integrated IRIS facilities can contribute to both general and site-specific (e.g., Alaska, Cascadia) multidisciplinary research. This theme of the maintenance and evolution of integrated facilities serving integrated, multidisciplinary science provides a consistent thread throughout this proposal.

Proposal Highlights

Over the past 7.5 years, 15 great earthquakes ($M_w \geq 8.0$) have struck globally, with some causing unprecedented devastation and loss of life, and all of them prompting evolution of our understanding of how major earthquake ruptures occur. The December 24, 2004, Sumatra (M_w 9.2) and March 11, 2011, Japan (M_w 9.0) earthquakes generated remarkable

Results of Prior NSF Awards

The following are the two NSF awards most relevant to this proposal. Funding shows amounts awarded to August 2012.

Results of Prior NSF Support: EAR-1063471, $26,384,286, Facilitating New Discoveries in Seismology and Exploring the Earth: The Next Decade (D. Simpson, PI), 10/1/11–9/30/13

With support through previous awards from the Earth Science Division, Instrumentation and Facilities Program, IRIS has established, maintained, and developed a wide range of facilities to support research and education in seismology and the Earth sciences. The IRIS Data Management System archives and freely distributes data from the Global Seismographic Network and the Program for Array Seismic Studies of the Continental Lithosphere. These data are a primary resource for national and international research and these IRIS facilities have helped sustain the US position as a global leader in seismology research. Through collaborations with national and international mission agencies and organizations, IRIS data contribute to the monitoring of global earthquakes, tsunamis, and nuclear explosions. IRIS Education and Public Outreach programs encourage careers in the Earth sciences, inform the public of current earthquake activity, and provide visibility to NSF's investments in support of geoscience research. The broad reach of the Consortium's governance structure, and the active engagement of research scientists in guiding the management of IRIS programs, continue to ensure that the facilities meet the evolving needs of the academic research community.

Results from Prior NSF Support: EAR-0733069, $73,609,490, EarthScope Facility Operation and Maintenance, (D. Simpson, R. Woodward, PI's), 10/1/08–9/30/13

IRIS has partnered with UNAVCO to develop and maintain the observational facilities to support EarthScope, a multidisciplinary Earth science initiative to study the structure and evolution of the North American continent and the physical processes responsible for earthquakes and volcanic eruptions. Initial funding for construction of the EarthScope facilities (2003–2008) came from NSF's Major Research Equipment and Facilities Construction account, and support for operations and maintenance since 2008 has been provided through the EarthScope program. IRIS has been responsible for the creation and operation of USArray as the seismic component of EarthScope. USArray consists of a nested set of seismic observational systems, including contributions to a national backbone of permanent observatories (as part of the USGS National Network); a Transportable Array of 400 stations that has systematically traversed the continental United States on a 70 km grid of more than 1600 locations, and a Flexible Array of more than 2000 broadband and short-period instruments for use in PI-led projects. An array of magnetotelluric instruments provides data for use in studies of the lithosphere's electrical structure. The data from all USArray instruments are freely and openly available through the IRIS Data Management Center.

tsunamis and demonstrated the need for and value of tsunami warning systems linked to rapid earthquake quantification. These events also demonstrated the flaws in some earthquake hazard assessment procedures, and are influencing global risk assessments. Surprises have been offered in terms of where great earthquake slip has occurred, with the April 1, 2007, Solomon Islands earthquake (M_w 8.1) rupturing right across a triple junction where a ridge is subducting, and the February 27, 2010, Chile rupture (M_w 8.8) having its largest slip in regions outside of the seismic gap that had been expected to fail. Great earthquake doublets have involved triggering of intraplate faulting by interplate failure in the Kuril Islands, and vice versa in the Samoa-Tonga region. The April 11, 2012, Indo-Australian earthquake sequence (M_w 8.6 and 8.2) involved the largest strike-slip faulting and largest intraplate faulting event that has ever been seismically recorded. Extensive seismic wave analysis of these events using both short-period signals recorded in large aperture arrays and global body and surface wave observations from IRIS and the International Federation of Digital Seismograph Networks (FDSN) stations indicates that five en echelon and conjugate faults ruptured during the two largest events. Such remarkable complexity would have gone unrecognized without availability of global, on-scale broadband seismic recordings.

The facilities operated by IRIS and funded by NSF have contributed in fundamental ways to our ability to tease out the complex details of faulting during the 2–10 minutes of rupture in these great events. The density of high-quality, permanent Global Seismographic Network (GSN) and FDSN stations provide the core data to unravel the faulting geometry and time history of rupture. Denser arrays, such as EarthScope's USArray Transportable Array (TA) and other high-density networks in Japan and Europe, make it possible to observe the spatial and temporal release of energy. In those places where dense networks of Global Positioning System (GPS) instruments are available, such as Japan, the merged analysis of seismic and geodetic data has increased the resolution of dynamic and static offsets. With the large volume of data being delivered from global seismic networks in real time, these resources, many of them initiated by IRIS, have also led to significant improvements in real-time reporting of earthquakes and substantially improved the ability to provide rapid warning of impending tsunamis.

In this proposal, we request support to continue to maintain and improve operation of the Global Seismographic Network, in collaboration with the US Geological Survey and many international partners, as a foundation network for global earthquake monitoring and research. As part of an overall IRIS initiative in quality improvement and tracking, special emphasis will be placed on improvements in GSN data quality and revitalization of ultra-broadband sensors. We will also explore the design, enhancement, and application of arrays such as the USArray Transportable Array to study the rupture of great earthquakes *and provide higher-resolution images of Earth's deep interior, and encourage their development and implementation in collaborative projects worldwide.*

One of seismology's underlying strengths has been international collaboration in data exchange for both earthquake and tsunami monitoring and fundamental research on earthquakes and Earth structure. The IRIS Data Management Center has become the de facto international archive for high-quality digital seismic waveform data and the source of choice for national and international researchers. An essential component of achieving and sustaining this role as international leader in data exchange has been the development of a variety of powerful and user-friendly tools for data collection, data archiving, data distribution, and quality assessment. The IRIS Data Management System (DMS) has initiated a series of international metadata workshops that provide instruction and training on modern best practices in data collection and archiving.

In collaboration with the University of Chile, a backbone network of 10 Global Reporting Observatories has been established in Chile with support from an NSF Major Research Instrumentation award to IRIS (Figure Intro-2). This network, based on USArray Transportable Array technology and experience, is an important asset for earthquake monitoring in Chile and provides a high-quality resource for detailed studies of subduction zone processes along the Andean arc. The network also greatly increases the coverage for monitoring earthquakes throughout the Southern Hemisphere. The productive interaction with Chile has involved the development of the backbone network, a unique international collaborative effort to deploy a temporary network following the 2010 M8.9 Maule earthquake, and the expansion of collaborative research with US scientists. These efforts provide a model for other international collaborations, especially in developing countries, that can be used to enhance both indigenous earthquake hazard assessment as well as the acquisition of data and resources that contribute to fundamental research efforts.

In this proposal, the extensive IRIS Data Services in data archiving, distribution, and product development, and the underlying commitments to free and open access and quality review, will be strengthened. We request support to continue IRIS leadership in encouraging and strengthening international collaboration in data exchange, and to assist in the development of high-quality regional and national networks for earthquake monitoring. Through training provided to local operators on network operation and data management, we can provide value-added leverage to substantially increase the quantity and quality of data available for research and, at the same time, contribute to national and regional programs in earthquake hazard assessment and mitigation.

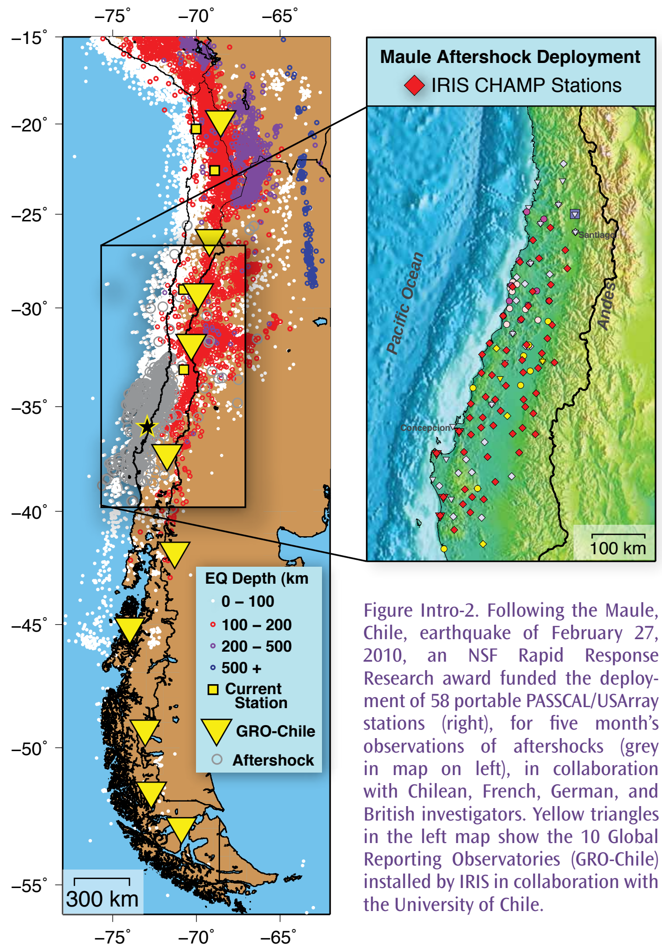


Figure Intro-2. Following the Maule, Chile, earthquake of February 27, 2010, an NSF Rapid Response Research award funded the deployment of 58 portable PASSCAL/USArray stations (right), for five month's observations of aftershocks (grey in map on left), in collaboration with Chilean, French, German, and British investigators. Yellow triangles in the left map show the 10 Global Reporting Observatories (GRO-Chile) installed by IRIS in collaboration with the University of Chile.

The recent spate of great earthquakes has increased concern in the United States about the potential for similar megathrust events along the Cascadia subduction zone in the Pacific Northwest and along the Aleutian Arc in Alaska. EarthScope resources, both USArray seismic stations and Plate Boundary Observatory (PBO) geodetic and strain instruments, have been deployed along the Pacific Northwest from northern California to southern Canada, and have been recently supplemented with the installation of ocean bottom seismographs off the coast of Oregon and Washington. A variety of multidisciplinary observations are being acquired, including data that document episodic tremor and slip. These data are revolutionizing our understanding of processes within subduction zones, which are potentially related to how deformation and slip evolve prior to great earthquakes. As USArray extends into Alaska, these joint USArray/PBO observations will be expanded, and collaboration with NSF's Geodynamic Processes at Rifted and Subducting Margins (GeoPRISMS) program will further extend the multidisciplinary planning and implementation of these observational programs and research.

In this proposal, we will continue to operate onshore USArray stations in Cascadia through the planned completion of the NSF

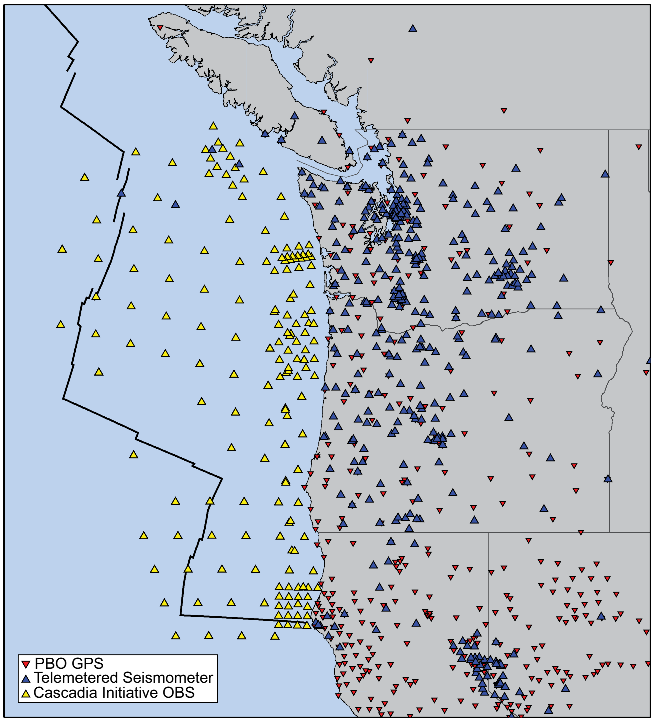


Figure Intro-3. Recently or presently operated stations throughout the Cascadia margin. The entire planned deployment of the Cascadia Initiative Ocean Bottom Seismometer (OBS) Experiment (2011–2015) has been represented. Real-time seismic and geodetic stations associated with EarthScope and regional operators are also represented.

Division of Ocean Sciences-funded ocean bottom observations in 2015. Existing EarthScope PBO resources in Alaska will be enhanced with the installation of USArray Transportable Array stations and the availability of portable instruments for special studies along the Aleutian subduction zone. IRIS and UNAVCO will collaborate on exploration of how the EarthScope experience can be applied to future large-scale international experiments along other major subduction zones. (Figure Intro-3)

At a different scale, earthquake activity in the past decade has also risen significantly in the United States. Clusters of small to moderate magnitude events in California, Texas, Colorado, Oklahoma, Arkansas, Ohio, and elsewhere have been related to various forms of human activities tied to fluid injection into the crust, including waste fluids associated with gas recovery following hydraulic fracturing. The coincidental timing of the advance of USArray's Transportable Array across the United States and the rise in energy prices that stimulated the energy sector's recent increase in domestic hydrocarbon recovery has been fortuitous. It has meant that a number of the triggered earthquake episodes have occurred within or near the Transportable Array footprint, allowing Transportable Array data to contribute substantially to the accurate location of these events and link them to the injection process. In addition, rapid, temporary deployments of dense networks of IRIS Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) instruments near clusters of induced earthquakes in Texas and Oklahoma have allowed even more-detailed studies of the extent of the seismicity and their relationship to disposal wells. Transportable Array recordings of moderate-sized mid-continental earthquakes are also providing quantitative data to predict the propagation of strong ground shaking during rare but potentially damaging larger events in the central and eastern United States.

On August 23, 2011, an M5.8 event in central Virginia shook the area around Washington, DC, and was felt widely across the northeastern United States. This earthquake was one of the strongest in the eastern United States to be recorded by modern instrumentation. It produced accelerations that exceeded the design specifications at a nearby nuclear power plant and caused damage within the Washington, DC, metropolitan area, more than 100 km away. Portable instruments were quickly deployed to the epicentral area (and have remained there for more than 10 months) to locate aftershocks. USArray provided 208 high-frequency Texan instruments to test the concept of high-density recording of an aftershock sequence with the short-term deployment of these instruments in a tight array to dramatically improve earthquake hypocenter locations, which in turn will help define the causative fault and provide critical information on local crustal structure (Figure Intro-4).

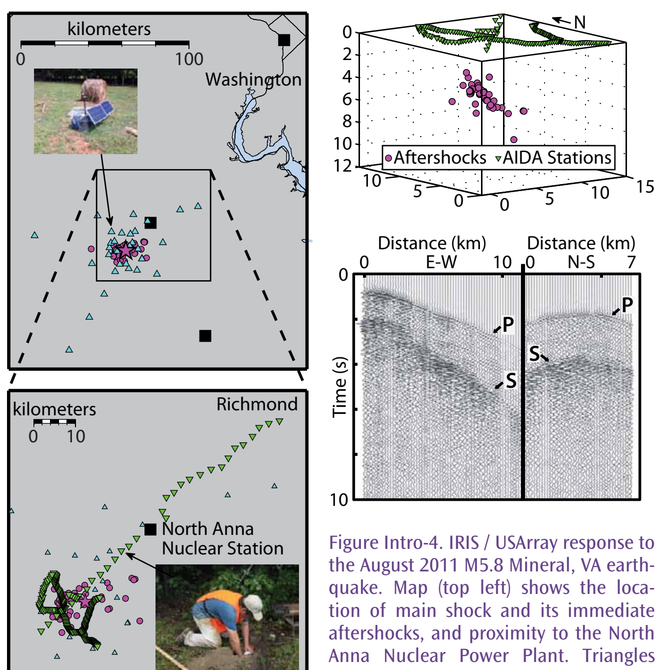


Figure Intro-4. IRIS / USArray response to the August 2011 M5.8 Mineral, VA earthquake. Map (top left) shows the location of main shock and its immediate aftershocks, and proximity to the North Anna Nuclear Power Plant. Triangles (blue) indicate stations deployed as part of a coordinated effort between the IRIS, USGS, Virginia Tech, Lamont Doherty Earth Observatory, and University of Memphis immediately following the earthquake. The inset map shows the Aftershock Imaging with Dense Arrays (AIDA) deployment (green) of USArray FA Texan seismometers deployed by Virginia Tech and Cornell Universities to locate aftershocks and image the fault region. The AIDA-located aftershocks delineate the fault surface (three dimensional volume, upper right). The AIDA seismograms (bottom right) show the P- and S-waves from an aftershock moving across the AIDA stations (AIDA results courtesy of John Hole).

In this proposal, we request support to (1) continue to provide instrumentation for rapid-response deployments following significant earthquakes and (2) develop a new generation of portable instruments with enhanced capabilities that will lead to fundamental changes in field deployments for high-resolution aftershock studies and imaging of Earth's interior. As part of a separately funded NSF initiative, it is anticipated that a subset of the USArray Transportable Array stations will be retained in the central and eastern United States to enhance the recording of natural and induced seismicity, and to provide information on ground motions important for re-evaluation of the design criteria for significant engineering structures, such as nuclear power plants.

On April 28–29, 2012, more than 150,000 people, mainly school-age children and their families, flocked to the Washington, DC, Convention Center to visit the second USA Science and Engineering Festival. Most of those from the Washington, DC, area had felt the Virginia earthquake eight months earlier and they were eager to learn more about earthquakes and seismology at the booths hosted by IRIS and EarthScope. At this and other public forums, such as meetings of the National Science Teachers Association, the Society for the Advancement of Chicanos and Native Americans in Science, the American Geophysical Union, and the Geological Society of America, IRIS Education and Public Outreach (EPO) engages the public, teachers, and students in learning more about earthquakes and seismology. Through web-based products, such as Recent Earthquakes Teachable Moments and USArray Ground Motion Visualizations, EPO uses newsworthy earthquakes as another way to attract the public to the Earth sciences.

In this proposal, we request support to continue to provide the public and educators with instructional and outreach resources related to seismology and the Earth sciences. Earthquakes and their effects are of great interest to the public and educators and provide a natural pathway for engaging a broad sector of the community and to encourage careers in the geosciences. (Figure Intro-5)

Our understanding of the origin of earthquakes and other natural hazards, of the nature and origin of mineral and energy resources, and of humanity's interaction with the environment depends intimately on our knowledge of the structure and composition of Earth's interior. Seismic waves traveling through the planet's interior are used to provide highly detailed images of it. IRIS data and instrumentation provide the fundamental observational underpinning for most of the seismological research on Earth structure funded by NSF and contribute strongly to earthquake and nuclear explosion research carried out by other US government agencies (US Geological Survey [USGS], Department of Energy [DOE], Department of Defense, and the National Oceanic and Atmospheric Administration [NOAA]), international universities, and intergovernmental organizations.

Figure Intro-5. Andy Frassetto of IRIS explains the concept of building resonance to families visiting the IRIS booth at the 2012 USA Science and Engineering Festival.

Since its founding in 1984, PASSCAL has fundamentally changed the way in which teams of individual scientists have designed and implemented portable field programs for US and global studies of both Earth structure and earthquakes. The IRIS model of multi-user, community-governed facilities has provided individual investigators with a wide range of equipment for use in a variety of portable experiment styles. This instrumentation covers the complete seismic spectrum, ranging from long-term "passive" deployments of tens to hundreds of instruments for earthquake observations, to short-term deployment of hundreds to thousands of instruments for "active-source" imaging of the lithosphere.

With the advent of EarthScope, the seismological resources available for studies of the structure of both North America and selected regions of the deep Earth have expanded multifold. USArray Flexible Array (FA) instruments have almost doubled the inventory of stations available for temporary experiments. The expansion of USArray to include magnetotelluric instruments has opened up new opportunities for multidisciplinary investigations that include both the seismic and electrical properties of the lithosphere.

In this proposal, we request support to continue to operate the merged pools of PASSCAL and USArray Flexible Array portable seismic equipment and magnetotelluric systems primarily in support of NSF-funded research. Currently, these programs support about 70 seismic field projects per year, most of them funded by NSF. None of this science could be achieved using only instruments owned by individual Principal Investigators. Continued support of IRIS Portable Seismology is essential for seismic research by US scientists.

One of EarthScope's major impacts has been the increased ability, provided by the USArray Transportable Array, to image lithospheric structure beneath the United States. This success highlights the way in which the US academic geoscience community has again revolutionized the implementation of a multi-user facility resource for seismological observations. The quality of Transportable Array operations has been exceptional in providing low-noise, wide-bandwidth, high data return. In addition to being used in the systematic application of well-established techniques for structural studies, such as receiver functions, shear wave splitting, and surface wave inversions, the unique aspects of the Transportable Array, in terms of uniform data quality and gridded array design, have stimulated a number of innovative and powerful new techniques, including ambient noise analysis for investigations of lithospheric structure and back projection array analysis to study the source dynamics of large earthquakes. The recent addition of atmospheric pressure and infrasound sensors to all Transportable Array stations opens up new opportunities for interdisciplinary studies of interactions between the atmosphere and solid Earth.

While data from the GSN and associated stations of the FDSN traditionally provided the primary resource for whole Earth modeling, there is increasing application of USArray Transportable Array data, and the "re-use" of data from all available broadband deployments, for high-resolution investigations of deep Earth structure.

In this proposal, we request support to complete the operation of the USArray Transportable Array in the northeastern United States and to provide the major investment required to install Transportable Array stations in Alaska, completing the 15-year seismic component of the original EarthScope plan. Under the new IRIS Instrumentation Services structure, the Transportable Array and the portable instrumentation mentioned earlier will be closely coordinated with specialized instrumentation and services provided for seismological and glaciological studies in polar regions (funded under this proposal through supplementary funding from the NSF Office of Polar Programs) and with newly established IRIS responsibilities for management and coordination of the NSF National Ocean Bottom Seismograph Instrument Pool (separately funded by the NSF Division of Ocean Sciences).

In the following sections of the proposal, we provide a summary of some of the significant scientific advances that have accrued based on the use of the seismological resources funded by NSF and managed by IRIS, an overview of the collaborative efforts by IRIS and UNAVCO in support of the EarthScope program, a brief description of IRIS governance and management structures, and descriptions of each of the service and operational units managed by IRIS, with identification of the activities proposed for support under this proposal.

Proposal Goals

The primary goals set out in this proposal are:

- ***Maintain and improve the core IRIS seismological facilities.*** The core facility resources that have accrued from NSF investments in the IRIS core programs (GSN, PASSCAL, DMS, and EPO) are essential resources for the seismological research and education communities. Under this proposal, management of these resources will be merged with EarthScope's USArray and funds are requested to continue to provide these communities with the high-quality data and instrumentation resources that they rely on for their research and teaching. We will continue to enhance user services and, with sustained community leadership and advice, explore new opportunities to improve and expand these resources.
- ***Complete the EarthScope facility plan.*** In collaboration with UNAVCO's efforts under PBO, and with leadership from the EarthScope Science Steering Committee, IRIS will, during 2013–2018 continue to support the facility efforts required to implement the EarthScope science program. With the completion of installation of Transportable Array stations in Alaska by 2018, the initial design goals of EarthScope USArray will have been achieved. An important aspect of IRIS joint efforts with UNAVCO and the EarthScope Science Steering Committee and the broad EarthScope community will be to explore ways in which the experience of EarthScope can be used to leverage new multidisciplinary research efforts.
- ***Educate our community and the public.*** The IRIS EPO program will continue to bring the excitement of seismology, earthquake studies, and the national reach of EarthScope to the public and the classroom, and highlight the value of NSF investments in research and in the Earth sciences. An increasing emphasis on undergraduate education, coupled with a very successful internship program, will expose students to seismological research and inspire careers in Earth sciences.
- ***Look to the future.*** While the primary emphasis of activities will be to sustain the existing facilities managed by IRIS, constant review and renewal is required to ensure that the facilities IRIS provides to support seismological research remain in sync with evolving and new research opportunities. Investments will be made in the development of portable instrumentation and in the enhancement of data resources to ensure that the US seismology community continues to have access to state-of-the-art instrumentation and data services into the future.

Scientific Justification

Several recent Earth science plans—about seismological grand challenges, EarthScope science, earthquake resilience, and the broad sweep of the Earth sciences—collectively set forth challenges and opportunities for seismology. Seismology plays a key role in addressing an overall goal of developing a fundamental scientific understanding of Earth system dynamics as well as more strategically motivated societal issues. In this section, we summarize some of the key points from these science plans and articulate how IRIS will provide the critical facilities, data, products, and services required to meet the challenges and take advantage of the opportunities.

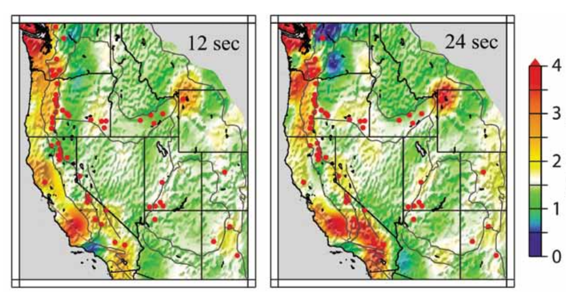
Geosciences and a few other scientific fields, such as cosmology and evolutionary biology, require close consideration of "deep time" and the profound changes that can accrue from slow processes. The pace of some of these processes—so slow that changes may seem negligible even over human history, yet quick enough that advanced systems can reliably measure differences over just a few tens of years—simultaneously creates challenges and opportunities. Examples of such Earth processes include the dynamic evolution of fault systems, changes in atmospheric chemistry throughout Earth history, charging and depletion of aquifers, sometimes sudden and irreversible changes in ocean circulation, and glacier dynamics that are coupled to insolation, precipitation, sea level, and isostatic rebound. As outlined in *New Research Opportunities in the Earth Sciences* (NRC, 2012), a predictive understanding of these processes and the ability to inform the most effective related policies in broader society are founded on collecting data that span time periods much longer than most laboratory experiments. Important scientific and societal objectives require both collecting "the same data" year after year through reliable long-term operation of facilities, and continually improving the facilities to enable new modes of research.

Through nearly two decades near the end of the twentieth century, IRIS built facilities to collect and manage modern seismological data—almost exclusively as part of Cooperative Agreements with the National Science Foundation. NSF funded and oversaw creation of this new generation of facilities partly because several technological advances, including feedback electronic circuits and digital data storage, enabled a revolution in seismology. *Seismological Grand Challenges in Understanding Earth's Dynamic Systems* (Lay, 2009) describes how investigations using these facilities will continue to exemplify the Foundation's core mission of discovery, innovation, and cutting-edge research.

While the USArray component of EarthScope represents a mature use of these technologies, *Unlocking the Secrets of the North American Continent* (Williams et al., 2010) anticipates a rapid and accelerating pace of discovery in seismology and related fields of Earth sciences—taking advantage of ongoing development of new ways to process the data and extract additional information, accumulation of data for a sufficient time span to measure secular changes, and measurements of a small, but growing, number of very large earthquakes. Extending these extraordinary achievements requires exploiting the latest technological developments, such as micro-electro-mechanical systems (MEMS) and other sophisticated electronics, new battery and power systems, and wireless communications. Moreover, computing and numerical methods have now progressed to the point that simulation has become an integral part of modern Earth sciences—particularly for seismology and geodynamics—and large, high-performance computing resources will enable three-dimensional predictions at the resolution needed to match observations of deformation, uplift, subsidence, and flow patterns across a range of scales from meters to thousands of kilometers.

Ambient Noise Tomography

Continuous seismic data, such as those collected by EarthScope's USArray and available at the IRIS Data Management Center, facilitate the use of ambient noise as a powerful probe of Earth structure. Background noise contains seismic waves that propagate coherently across arrays of seismographs. By correlating the recordings at two stations and averaging over long time periods, a coherent signal can be extracted, yielding measurements of seismic waves propagating from one station to the other. By combining noise data from many station pairs, a 3D tomographic image of subsurface velocity structure can be constructed. Even more recent advances include methods to determine anisotropy, attenuation, and temporal changes.

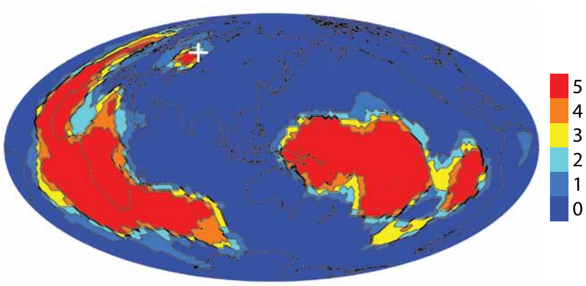


Attenuation coefficients across the western United States inverted from 12 s (left) and 24 s (right) period ambient noise. Geologic terrain boundaries (thin black lines, with labels) and Holocene volcanoes (red circles) are plotted for reference. High attenuation and low phase velocity (not shown) are observed along the margins of the Colorado Plateau, along the Rio Grande Rift, and beneath Yellowstone. *(Lawrence and Prieto, 2011)*

Seismology plays key role in addressing many needs of broader society, including energy resources, environment, national security, and several natural hazards. In no area, however, are the uniquely important impacts from seismological research more evident than in addressing earthquake hazard. *National Earthquake Resilience: Research, Implementation, and Outreach* (NRC, 2011) details how seismologists must contribute by making near-field measurements to understand the physics of earthquake processes; evaluating and testing earthquake early warning systems and methods for operational earthquake forecasting; completing national seismic hazard maps and creating urban seismic hazard maps; enabling robust coupled simulations of fault rupture, seismic wave propagation, and soil response to reliably estimate losses and casualties; and contributing to scenarios so that communities can visualize earthquake impacts.

Lowermost Mantle Global Structure

Seismologists are collaborating with geodesists, geodynamicists and materials scientists to determine density, temperature and other mantle properties that cannot be measured from seismic wavespeeds alone (Simmons et al., 2010). This progress comes, in part, from resolving the structure of large, low-shear velocity provinces at the base of the mantle with the accumulation of high-quality broadband data from the GSN and its international counterparts, as well as dense PASSCAL and USArray deployments. This work brings out the distinct average velocity profiles within and outside irregularly shaped high- and low-velocity provinces in the lowermost mantle. Modeling of broadband waves that propagate along and across the province borders show that they are sharp, indicating that the distinctive properties cannot be due only to temperature differences. If large, chemically distinct reservoirs continue to exist in the mantle, then occasional reorganization of mantle circulation could profoundly alter cycling of volatiles between Earth's interior and the ocean and atmosphere.



Independent models of global shear wave speed in the lower mantle are in increasingly good agreement. This map is composed of bins that are color-coded according to how many of five well-regarded models have a V_S profile that cluster analysis identifies as distinctly slow. The analysis demonstrates consensus on two large low-shear wave speed provinces, the African and the Pacific, within a single, globally contiguous faster-than-average lower mantle. *(Lekic et al., submitted)*

In what follows, a set of key questions derived from *Seismological Grand Challenges in Understanding Earth's Dynamic System* (Lay, 2009) is used to illustrate the ways in which seismology, and the resources provided by the IRIS facilities, contribute to a broad range of topics that enhance our understanding of fundamental Earth processes and the ways in which they impact our lives.

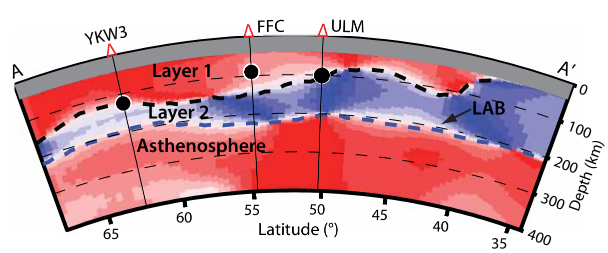
Thermo-Chemical Internal Dynamics and Volatile Distribution

How do Earth's temperature, composition, and internal boundaries control mantle and core dynamics and the changing morphology of our living environment? How do the lithosphere and plate boundary systems evolve over Earth history?

The solid Earth is a complex and dynamic system with processes that operate over spatial scales from nanometers to tens of thousands of kilometers and time scales from

The Lithosphere-Asthenosphere Boundary and Plate Tectonics

High-fidelity broadband records over long time spans at GSN stations and on dense spatial arrays from PASSCAL and USArray deployments have led to the surprising discovery of discontinuous decreases in seismic wave speeds at depths of 50 to 130 km (Rychert and Shearer, 2009). In the ocean and in tectonic areas, this discontinuity is likely related to the lithosphere-asthenosphere boundary. But the discontinuity is also observed midway through old continental lithosphere, where it is associated with a several layers of distinct heterogeneity and anisotropy measured from long-period surface wave and overtone waveforms and SKS splitting data. Understanding this structure, which is difficult to explain through normal thermal mechanisms, will lead to fundamental new understanding of how melting is distributed within Earth, how plate motions affect and are influenced by variations in composition and rock fabric, and how continents are formed.



Cratonic cross section showing the departure of the fast axis of azimuthal anisotropy from the direction of absolute plate motion (APM) of the North American Plate in the hotspot reference frame. The mid-lithospheric discontinuity occurs in the depth range where a low velocity layer is detected from receiver function studies (black dots). *(Yuan and Romanowicz, 2010).*

nanoseconds to billions of years—controlling geothermal evolution, driving long-term continental development, generating Earth's magnetic field, and cycling volatiles between the interior and the ocean and atmosphere. Seismological measurements from the GSN continue to provide key information on global Earth structure. The USArray Transportable Array (TA) is demonstrating the power of a densified station deployment, and portable (PASSCAL and Flexible Array [FA]) deployments have allowed yet higher resolution of features of key interest. Progress on understanding the solid Earth system comes from a variety of disciplines, but seismology is critically situated because it best resolves their present configuration and near-term evolution. There is an ongoing need for the diverse components of seismological infrastructure in order to improve and test our ideas of how Earth systems operate. IRIS Data Services ensure quality, compatibility, and long-term security of these data so that the rate of discovery grows even more quickly. Recent improvements in wave imaging, modern sensor technology, and the computational capability available to model large, dense waveform data sets motivate both new observational strategies for seismology and development of products, services, and simulation capabilities to accommodate the substantial computational demands of modern geodynamics, seismology, geomagnetism, and mineral physics.

USArray data are already providing unprecedented resolution in addressing questions about how mountain building, lithospheric deformation, and volcanism across the western United States have been influenced by tectonic history and the existence of the subducted lithospheric slab in the upper mantle. As the TA continues eastward, as the number of FA experiments in the eastern United States grows, and geophysicists and geologists start new collaborations, Earth scientists will investigate and illuminate the history of the North American craton from its formation to the present. North America has progressively grown through a punctuated history that includes two full cycles of continental collision, accretion, and rifting, and this history is written in the rocks. Some past geologic events resulted in mineral and fossil fuel deposits that are being exploited today. Processes currently occurring at great depth beneath the western United States cannot be directly observed but have signatures in rocks that have been uplifted and exposed in the older mountain belts of the eastern United States. Questions that we can answer specifically about this continent—Why did the Midcontinental Rift System fail to split North America? What was the nature of deformation during past closing and opening of the Atlantic Ocean?—will provide insight into processes that operate globally.

In Alaska, TA stations and FA deployments will enable direct investigation of the diverse tectonics across a broad region, and additional insight into the thermo-chemical dynamics. Among many other objectives, better imaging of a nearly flat subducted slab that underlies a large part of Alaska will complement studies of analogous lithospheric evolution in the western conterminous United States during a critical period, the Laramide orogeny (~70 million years ago), when the Colorado Plateau and present Rocky Mountains developed.

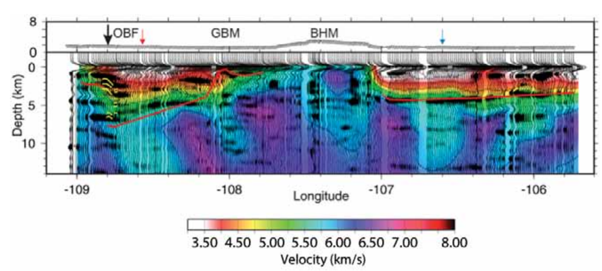
Faulting and Deformation Processes

What is the relationship among stress, strain, and deformation as expressed in earthquakes, slow slip, volcanic eruptions, and movement of fluids within the crust?

Deformation processes at scales ranging across orders of magnitude are relevant to mitigating geological hazards and understanding earthquake cycles, volcanism, and their interactions. The dynamics of the San Andreas Fault system, the Cascadia subduction zone, and deformation related to volcanic eruptions are being elucidated through FA studies. The eastern United States faces seismic hazards that result

The Merging of Active and Passive Source Seismology

Tomographic analysis of extraordinarily large sets of controlled-source data result in broad, high-resolution models of wave speed, while records of earthquakes at teleseismic distances provide complementary information. In novel processing methods, records from selected distant earthquakes are being used for "virtual source reflection analysis." Structural information is extracted from these data by deconvolving the source pulse, leaving an underside reflection that acts as a virtual source for subsequent reflections off crustal interfaces. Thus, active-source tomography captures the low velocities of the sedimentary basins, while teleseismic virtual source imaging reveals deeper structure.



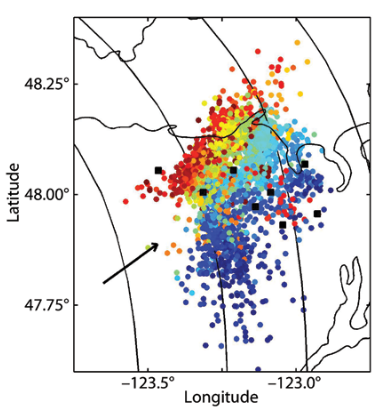
The EarthScope Bighorn Project is an interdisciplinary program ultimately to explain how orogens can happen near the middle of stable continents. The active seismic component used many hundreds of "Texan" seismic systems to record dozens of shots at a total of about 3000 recording sites, on a 2D grid that covered the entire Bighorn Arch. This virtual source reflection profile was made from earthquakes at teleseismic distances recorded on single-component geophones, superimposed upon a color background that represents P wave speed tomography from local controlled sources. Geophones are shown by small triangles plotted at station elevation. Red lines mark the top of the Tensleep formation; yellow lines are multiple reflectors near the Oregon Basin Fault (OBF). *(Yang et al., 2012)* from movement on geologic structures created by past tectonic events. The regularity and consistency of the TA make it possible to better understand these processes, which is required to assess if time-dependent seismic hazard estimates for sites of historical damaging earthquakes in central and eastern North America is even feasible. Our understanding will be widened with an enormous quantity of new data from the arc-trench system on the southern margin of Alaska, the active Aleutian volcanic arc, and the St. Elias Range where the Yakutat terrane collides with coastal Alaska.

The availability of thousands of inexpensive and easily deployed sensors and data acquisition systems in the FA pool has facilitated rapid progress in studying episodic tremor and slip, and motivated innovation in data processing such as new multibeam back-projection methods that have been used to map migration of tremors over days and weeks. Newly discovered classes of earthquakes and patterns of tremor and slip have profound and as yet only partially understood implications for understanding the physics of fault friction and slip.

Resonance in basins and focusing of seismic waves by surrounding structures are major contributors to geographic variability in earthquake shaking so, along with fault geometries, high-resolution three-dimensional structural maps are required to improve earthquake hazard models and strong motion simulations. Compared to typical state-of-the-art university-based seismology, the need for such maps across broad areas compels a larger investment and innovative adaptation of deployment strategies developed for commercial applications. For this application, controlled-source data from

Episodic Tremor and Slip

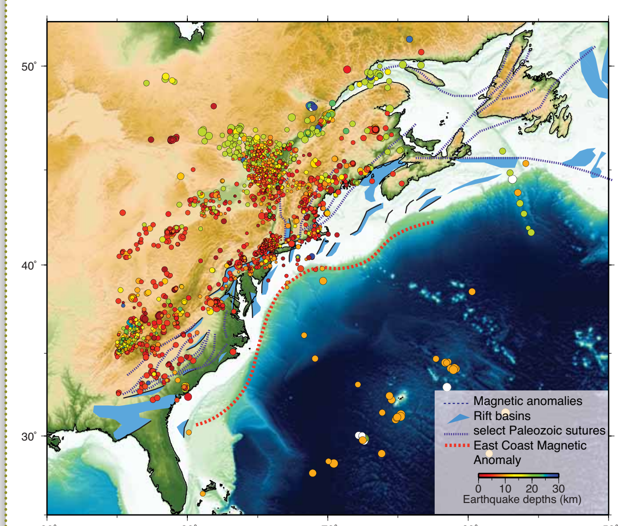
An exciting recent advance in seismology is recognition of a wide range of rupture behaviors in and near major faults zones, including "slow earthquakes" and regional seismic tremor synchronous with geodetically measured episodic slip. Seismic tremor was first recognized as a regional phenomenon, rather than a probably anthropomorphic effect at a single station, after deployment and joint analysis of dense regional arrays, such as the Transportable Array and dense permanent networks in Japan. The geodetic evidence shows tectonic slip many orders of magnitude slower and often deeper than "regular" earthquakes. Some tremor and slow slip events occur regularly with periods of months to years, others are aperiodic, and still others appear to be triggered by distant earthquakes, suggesting that deeper portions of the fault are only marginally stable.



High-resolution tremor locations from multibeam back-projection during a major four-day episodic tremor and slip event under northern Washington State. Each black square represents a subarray of seismic stations. Circles show tremor epicenters, colored to indicate the time of activity, from August 16 (dark blue) through August 19 (dark red). *(Ghosh et al., 2010)*

EarthScope and GeoPRISMS in Eastern North America

The arrival of EarthScope's Transportable Array on the East Coast, Flexible Array deployments underway and planned in the region, and availability of new geodetic data together present an important opportunities to vastly improve the resolution and accuracy of deformation models, more accurately map seismic attenuation, raise awareness of earthquake hazards, and motivate improved earthquake preparedness in eastern North America. The Implementation Plan for GeoPRSIMS identified eastern North America as a primary site for the program because the record of multiple Wilson cycles and significant along-strike geologic variations makes it an excellent place to study mountain-building processes, rift initiation, and the evolution, structure, and deformation of a passive continental margin. The M_W 5.8 earthquake near Mineral, VA, during August 2011 was felt over a larger region of the United States than any previous instrumentally recorded earthquake; it serves as a reminder that passive margins are tectonically active and that real seismic hazards on the East Coast are poorly documented.



The tectonic history of eastern North America is recorded in rift basins, suture zones, and other geologic structures. Evidence of the complex history is embedded in magnetic, gravity, and other geophysical anomalies, as well as numerous seismically active fault zones. *(Shillington and Meltzer, pers. comm.)*

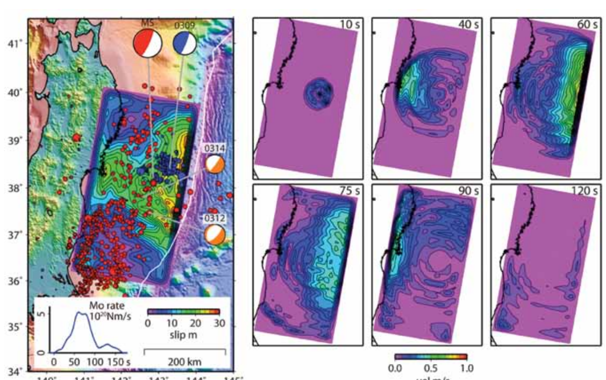
100 or more explosive shots include multiple crossing lines of refraction and low-fold reflection data from thousands of recorders, each deployed at multiple sites. Some studies also involve thousands of airgun shots and water bottom sensors in lakes, onshore-offshore data, and broadband stations.

Earthquake hazard in the central and eastern United States is a topic of growing concern for several reasons—including increased awareness following the magnitude 5.8 earthquake in Virginia during 2011, the likelihood of restarting construction of nuclear power plants (Andrews and Folger, 2012), and an apparently real increase in seismicity—exemplified by recent events in Texas, Arkansas, and Ohio—that might be due at least partly to fluid injection to store wastewater from hydrofracturing, to sequester carbon, or to extract geothermal energy. In addition to information from the TA and planned FA experiments in the eastern United States, recent portable deployments in Texas, Oklahoma, and Virginia have used different combinations of broadband systems and "Texans" for detailed source studies, fault mapping, and attenuation measurement to build on a foundation of improved regional coverage.

Large earthquakes are rare on any given plate boundary segment, but over less than 20 years of full-scale operation, the GSN has created records of hundreds of moderately large earthquakes as well as a handful of "great" and infamously deadly events. With these and other data, we are steadily improving our understanding of stress accumulation and release, of rupture initiation and propagation. Both fine-scale structure and regional wave propagation from complex rupture scenarios can be modeled with dedicated high-performance computing resources to accurately predict strong motions. The results include a capability to generate

Tohoku-Oki Earthquake

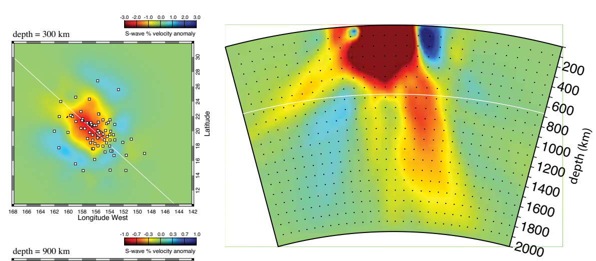
The Global Seismographic Network's earthquake recording capability played a critical role in understanding the extraordinary sequence of M ≥ 8.5 earthquakes during the past several years, in or near Indonesia (Sumatra, Nias, and Bengkulu), Chile, and Japan. With rapid advances in data processing, back projection imaging from seismic array data for these great earthquakes is now done quickly after large earthquakes (Kiser and Ishii, 2011), and has shown that seismic wave excitation is often strongly depth dependent, with high frequencies generated more efficiently down-dip and low frequencies dominating up dip. Several mechanisms have been proposed to explain different rupture behaviors, including pore-fluid pressurization, resistance from subducted seamounts, and combinations of dynamic nonlinear effects. GSN records from a wider range of such earthquakes are required to be confident of new inferences, and a Global Array of Arrays would enable higher-resolution imaging of future large earthquakes than is currently possible.

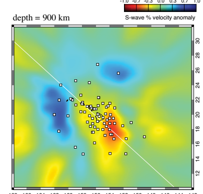


Total slip is contoured at lar, and shown with focal mechanisms of the foreshock, mainshock, and two normal-faulting aftershocks. Red symbols show the mainshock (star) and aftershocks (circles); blue symbols show the largest foreshock (star) and foreshocks (circles). The inset shows the moment-rate function. Snapshots of slip rate at different times during the earthquake are shown at right. *(Ide et al., 2011).*

Imaging Earth from the Seafloor

Measuring Earth properties beneath ocean basins is challenging because islands rarely offer sites for seismic arrays that are sufficiently dense to support modern approaches to seismic imaging, or sufficiently wide aperture to image the deeper parts of important structures. Investigators are overcoming this limitation with temporary ocean bottom deployments that are progressively more sophisticated, improving bandwidth, noise levels, dynamic range, and data return rates. Often, the best opportunities for science return arise from combined networks of ocean bottom and land seismic stations. These results can support or refute global tectonic hypotheses, such as hot spots resulting from high-temperatures plume rising from the lower mantle.





The PLUME project combined network of ocean bottom and island seismometers to collect data for three-dimensional images of shear-wave velocity beneath the Hawaiian Islands. In this cross section of S-wave velocities beneath Hawaii (from Wolfe et al., 2009), use of SKS arrivals in addition to direct S makes it possible to resolve features as deep as 1500 km, and suggests a region of low velocities beneath Hawaii that may be several hundred kilometers wide and extend down into the mantle transition zone, in agreement with other transition-zone thinning inferred from the much sparser network of permanent seismic stations. *(Wolfe et al., 2009)* realistic shaking scenarios for regional demonstration projects with physics-based simulations of damage and improved earthquake hazard and loss assessment. The development of such new insights is accelerated dramatically by earthquakes or eruptions of particular significance, but the timing of these events cannot be anticipated. Thus, we must be ready by operating a fiducial network of seismic observatories, maintaining state-of-the-art portable instruments that can be deployed rapidly when important earthquake and volcanic eruption sequences occur, and developing capabilities for rapid warning of earthquake shaking.

Change and Interactions Among Climate, Hydrology, Surface Processes, and Tectonics

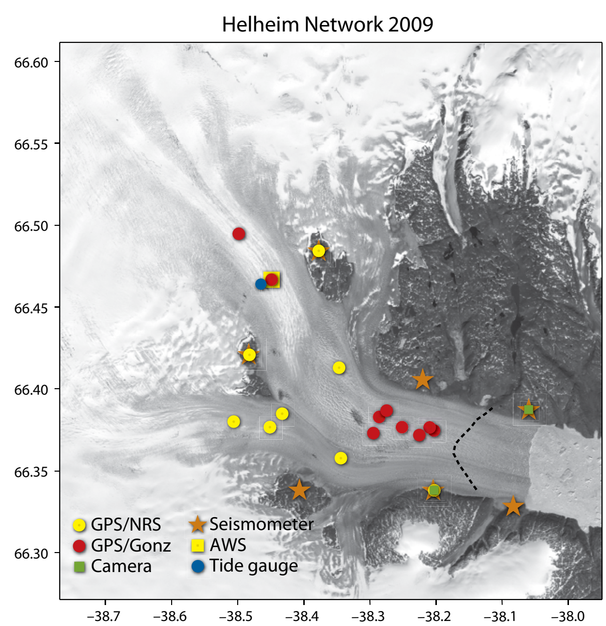
How do Earth dynamics and structure relate to the distribution of freshwater and energy resources? How do the coupled systems respond to natural and anthropogenic forcing?

Seismology has an overwhelmingly important role to play in the development of energy options for the 21st century, and is an important complement to other geophysical techniques in managing water resources. PASSCAL and FA deployments increasingly facilitate 3D seismic imaging at the reservoir and basin scales that are of central importance to oil and gas exploration and to optimal management of existing fields. Induced earthquakes monitored by networked instruments have had impacts on geothermal energy, where they have led to operations being shut down. Induced earthquakes have also had an impact on shale gas development where they have been implicated in operations to re-inject flowback water. If CO_2 sequestration is to happen at a scale to mitigate climate change, induced earthquakes are likely to place important constraints on that activity as well. The future of nuclear power plant construction and high-level radioactive waste disposal is critically dependent on developing a predictive understanding of earthquake behavior, particularly in areas of low seismic hazard.

A new generation of integrated power and data acquisition systems developed by experienced PASSCAL and UNAVCO engineers has facilitated growth and success of the Polar Earth Observing Network (POLENET)—a project to collect seismic and geodetic data from autonomous systems deployed at remote sites spanning much of the Antarctic ice sheet to answer critical questions about their behavior in a warming world. Combining these POLENET measurements with ground-based measurements of gravity, sea level, and the atmosphere and with satellite measurements will lead to better ice sheet budgets, link ice sheet change to the global Earth system, and provide a deeper understanding of how polar ice sheets contribute to changing sea levels around the world. IRIS's role in the Greenland Ice Sheet Monitoring Network (GLISN) has established a real-time array of seismic stations

Glacial and Iceberg "Earthquakes"

Recent deployments of broadband seismometers on ice sheets and icebergs have recorded breakup in the Ross Sea near Antarctica, calving of ice off the end of glaciers, and iceberg fracturing. The records are yielding new insights into these processes, which may be accelerating due to climate change. Glacial earthquakes were discovered recently as low-frequency signals in seismograms from the GSN. Many of the events that occur during the late summer along the coasts of Greenland are clustered near large outlet glaciers. The rate of glacial-earthquake occurrence varies from year to year, increasing quickly between 2000 and 2005 but continuing at a steady rate more recently. Variations in glacier-terminus position and retreat rate between seasons and between years account in general for variation in the rate of occurrence of glacial earthquakes. Seismological measurement of glacier and iceberg dynamics adds a new tool both for monitoring and for retrospective studies of 20th century activity, but on-site investigations to discover the mechanisms by which glacial phenomena generate seismic signals are needed to maximize returns from multidisciplinary data analysis.

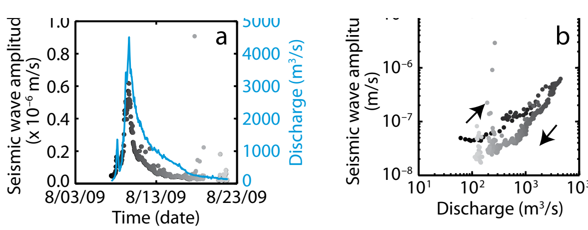


"Studies of Earthquakes and Rapid Motions of Ice" used PASSCAL and other instruments to focus on East Greenland's two largest outlet glaciers, Helheim glacier and Kangerdlugssuaq glacier. This map shows seismological, geodetic, photographic, and other systems used for local monitoring of Helheim glacier during the summer of 2009, collected in the field and via remote sensing, to build an understanding of flow dynamics and short-timescale glacier behavior. The data demonstrated that the times of glacial earthquakes are strongly correlated with large calving events, which result in rapid changes in glacier speed. The seismic signals were generated by impacts on the face of the glacier and the underlying solid Earth when cubic-kilometer-scale icebergs capsized. *(Nettles and Ekström, 2010)* to enhance and upgrade the infrastructure for characterizing glacial earthquakes and other cryo-seismic phenomena, and is contributing to our understanding of ice sheet dynamics. Complementing data from satellites, geodesy, and other sources, GLISN is a powerful tool for detecting change and is advancing frontiers of research in glacial systems, the underlying geological and geophysical processes affecting the Greenland Ice Sheet, and interactions among the ocean, climate, and cryosphere.

Through continuous monitoring by the GSN and federated FDSN stations, it has become apparent that there are seismic signals generated by interactions from the solid Earth with the ocean, atmosphere, and cryosphere. Here, seismology has the potential to provide unique insights into processes involving these complex and evolving systems that are increasingly susceptible to anthropogenic impacts. Within the last decade, seismologists have become adept at using microseisms generated by ocean wave action for several ends. Decadal variations of seismic noise show the signature of such large-scale climate variations as El Niño. Large glacial calving events show up seismically, as do episodic deformation transients from large Antarctic ice streams. PASSCAL experiments have been coordinated with ocean bottom seismometer deployments, ship-based seismic sources, and multichannel marine seismic surveys to make onshore/offshore seismology a key tool for mapping the subsurface in coastal environments—laying the groundwork for understanding and forecasting the response of coastal landscapes to sea level rise, climate change, and human and natural disturbance.

The Seismology of Rivers

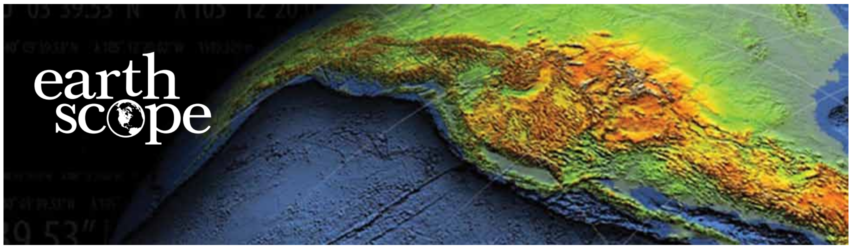
Rivers generate seismic waves as they rumble across the landscape. These waves directly record the stresses on the bed that contribute to carving river valleys. Recently geomorphologists have begun to exploit the seismic wave fields to glean information about these key pieces of the puzzle of landscape evolution. Observations from both portable arrays and permanent stations have shown that seismically recorded noise tracks water level both seasonally and within individual storm events. However, the details of the response function change over time with decreasing seismic wave responses after major storm events (Burtin et al., 2008; Hsu et al., 2011). The continuous probes of the natural system promise new insights into previously unattainable fundamental quantities.



In a typical storm event, the temporal variation of seismic wave amplitude (gray gradient dots) and discharge (blue curve) are highly correlated. Analysis of hysteresis in the amplitude/discharge relationships, such as that shown by the dot gradient (becoming lighter gray with time) and arrows in the right panel demonstrates that fluvial seismology can detect river bed evolution over storm timescales. *(Hsu et al., 2011)*

Conclusion

There are a wealth of opportunities to better understand our world and to serve broader society by mitigating hazards and utilizing resources—and a variety of challenges in making the best use of new technology to realize those opportunities. Several science communities have defined many specific targets for EarthScope and other seismological, geophysical, and geodetic facilities, but the next decade will also yield important unanticipated discoveries. Earth science facilities are producing data streams that are broad, deep, and accessible to all. IRIS-built seismological facilities were envisioned as tools to facilitate studies of the solid Earth and justified partly by their role in monitoring underground nuclear tests. But even while these applications continue to be important, the data are increasingly being used to map and measure a much wider variety of phenomena. Given the importance of the ocean, atmosphere, and cryosphere to the future of the planet in a changing climate, the role of seismology in understanding these systems is destined to grow, and seismologist must be prepared for that demand. Some of the most exciting discoveries, and perhaps those with the greatest impact on society, may come from scientists using seismological data, products, and services in new ways.



EarthScope

Exploring the Structure and Evolution of the North American Continent

EarthScope is an ambitious, multifaceted initiative to explore the structure, history, and dynamics of the North American continent, and is the world's first interdisciplinary continent-scale geophysical observatory. A broad and growing population of scientists utilize data collected by the EarthScope Facility to investigate processes that shape the Earth's geological architecture and landscape, as well as those that produce natural resources and natural hazards. EarthScope science bears on processes that operate from the sub-second to billion-year time scales, from individual earthquakes to stresses driving lithospheric plate deformation. EarthScope's target, the North American continent, provides a diverse range of geologic processes, yielding fundamental new insights into this dynamic planet.

Three interlinking components comprise EarthScope: (1) the EarthScope Facility (PBO, SAFOD, and USArray) jointly operated by the UNAVCO and IRIS consortia, (2) a scientific research program that supports PI-led investigations, and (3) an investigator community, coordinated by an academic EarthScope National Office (ESNO), which actively participates in science planning, research, and facility governance. The EarthScope stakeholder community, broadly defined, also includes formal educators (e.g., K–12 teachers, university faculty) and informal educators (e.g., interpretive Park Rangers, museum educators) who make use of the education and outreach resources and programs provided by IRIS, UNAVCO, and ESNO, including online science content, published brochures, teacher professional-development workshops, and interpretive workshops for park and museum educators. These education and outreach activities are intended to maximize the broader impact of EarthScope science.

The EarthScope Facility acquires, delivers, and archives data, develops data analysis protocols and products, provides engineering services for field instrument deployment, and organizes community forums. The EarthScope Science program at the NSF sponsors a broad range of PI-driven research and workshops, with a particular focus on multidisciplinary efforts that make use of EarthScope data sets. The EarthScope research community is a growing, broad, and diverse body, conducting innovative research, informal and formal education, and governance of EarthScope facilities. The continued vibrancy and success of EarthScope depends on the Facility for stability of operations and standards, on the research program for financial support, and on the science community as the energy source of innovation, discovery and communication.

EarthScope Observatories

The EarthScope Facility's three components include USArray, the Plate Boundary Observatory (PBO), and the San Andreas Fault Observatory at Depth (SAFOD). These components began construction and operation in 2003, and have evolved into an integrated system of mature and robust observing systems, providing fundamentally important datasets that have thrust researchers into new realms of data analysis and discovery as documented in the published literature and highlighted elsewhere in this proposal.

USArray has multiple observatory components: a Transportable Array (TA), a gridded network of 400 seismometers, barometers and infrasound sensors rolling across the lower 48 United States and parts of southern Canada deployed for ~2 years per site, a Flexible Array (FA), which includes more than 2,000 seismic systems available for PI-driven focused field experiments, and 20 magnetotelluric systems used for campaign deployments on discrete targets.

PBO includes more than 1,100 continuous Global Positioning System (GPS) stations distributed across the United States, and concentrated on the active plate boundaries in the western contiguous US and southern Alaska (Figure ES-1). PBO also includes 75 borehole strainmeters and 78 borehole seismometers deployed along the San Andreas Fault and above the Cascadia subduction zone and volcanic arc. Tiltmeters (26) and pore pressure sensors (22) are also collocated with the other borehole instruments. The integrated nature of EarthScope observations has been especially important in Cascadia, where broadband seismic observations from over 70 stations (27 of them established through

This section was prepared jointly by IRIS and UNAVCO, with input from the EarthScope Science Steering Committee, PBO Advisory Committee and USArray Advisory Committee, for inclusion in both proposals. Additional boxes, identified later in the proposal, were also prepared jointly to describe other areas of common IRIS and UNAVCO activities.

EarthScope) and high-rate, low-latency real-time GPS geodetic observations at 372 PBO stations are being supplemented with offshore observations at over 60 ocean bottom seismic stations and a number of temporary USArray FA deployments. Geodetic imagery and geochronology services supported under GeoEarthScope extend fault histories to millennial timescales.

SAFOD is a 3.1 km deep borehole penetrating the San Andreas Fault system near Parkfield, CA. Rock core was recovered during deep drilling sampled across the seismogenic zone, and is the focus of a variety of rock mechanics and related studies. At present a high-frequency seismometer is deployed and is maintained downhole by the USGS at SAFOD, recording a unique seismic data set at a depth of ~660 m below the surface. Under the current NSF-CA for PBO, UNAVCO manages both PBO and SAFOD. SAFOD management will transition to a newly established SAFOD Management Office (SMO) in coordination with NSF in the near future.

EarthScope Achievements

EarthScope has become an international community platform for the Earth Sciences. Data collected by the EarthScope Facility have supported groundbreaking science, including new discoveries in Earth's atmosphere, surface, crust, mantle, and core. Hundreds of published papers have used EarthScope data, and new results enabled by EarthScope are published weekly. EarthScope has enabled new data processing techniques as well as innovative visualization tools. EarthScope has enabled new discoveries that already mandate rewriting key portions of Earth Science textbooks.

While many of the fundamentally new results that rely on EarthScope data are discipline-based, some of the more exciting discoveries have emerged from EarthScope's goal of encouraging interdisciplinary studies that integrate geology, geodesy, seismology, geochemistry, geodynamics, and geophysics. EarthScope has encouraged a new generation of young scientists to start their careers in an interdisciplinary framework, and some of these scientists are now entering leadership positions within the scientific community. These efforts continue to challenge the community to maintain a broad scope of research activities. Ongoing EarthScope research support strengthens these research directions.

Some examples of the breadth of EarthScope discovery and transformative science include:

- Tracking, imaging and elucidating episodic tremor and slip (ETS) along the Cascadia and the San Andreas fault systems, characterizing this recently recognized mechanism that operates within the earthquake cycle.
- More precise constraints on surface deformation driven by slip along the San Andreas fault.

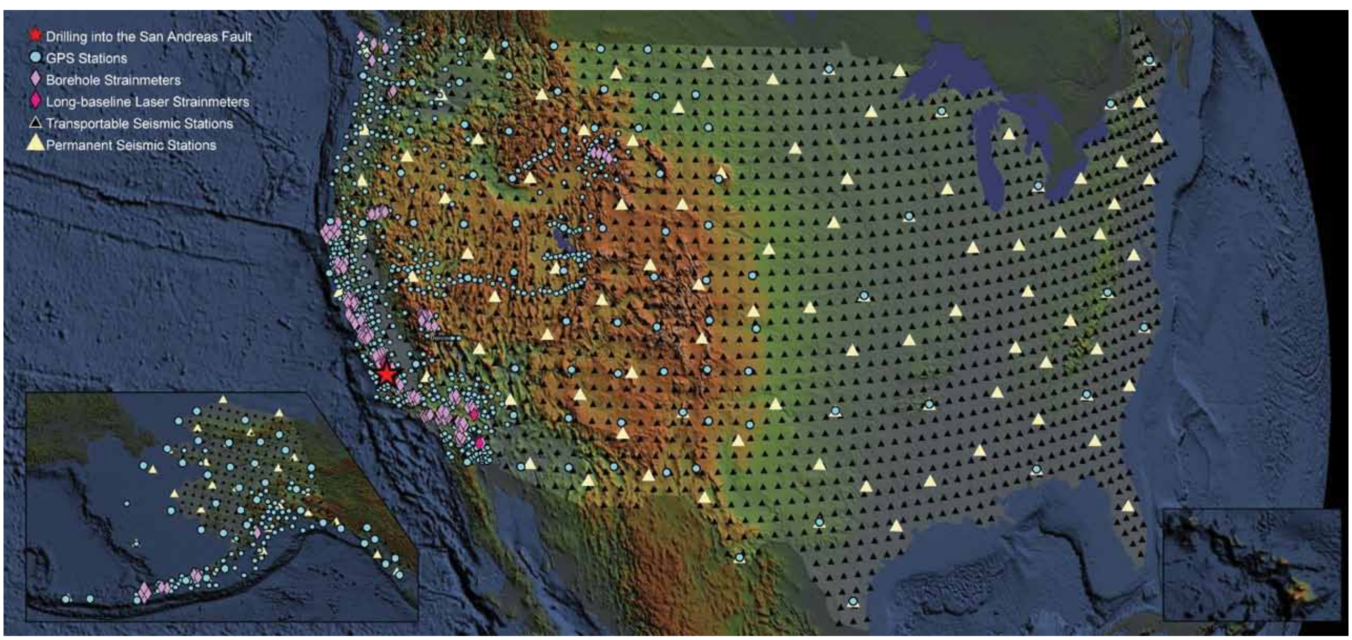
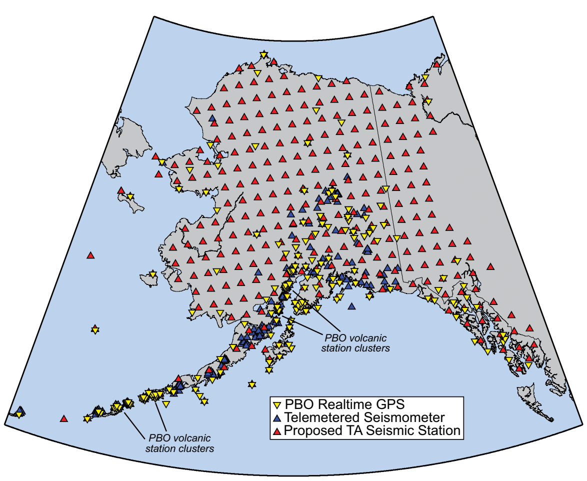


Figure ES-1. A map of the EarthScope Facility as envisioned in the early MREFC development phase showing the continental perspective and the multiscale and multiparameter observation systems. After a 10-year adventure, the design plan for EarthScope in the conterminous lower-48 is approaching full completion ("on-time and on-budget") and the USArray is preparing to embark to Alaska and complement Plate Boundary Observatory observations already underway there. The nominal USArray locations shown on the map (small and large triangles for Transportable Array and Reference Network stations, respectively) have all been installed essentially where proposed, at sites located by university students from across the country. The Reference Network was completed during the construction phase, and over 1,400 Transportable Array stations have been installed in year-round operations that have been ongoing since 2004 (this will be nearly 1,700 sites by September 2013 when the current award is complete). All data are archived and distributed via the IRIS Data Management Center. Hundreds of private landowners who have hosted USArray station sites continue to receive EarthScope newsletters. Not shown are thousands of Flexible Array station sites, at experiment locations spanning the United States, as well as over 360 magnetotelluric station sites. "As built" locations of the USArray station sites are shown in maps later in this proposal.

Alaska: A Geoscience Frontier

During 2013–2018, the collective observing power of EarthScope in Alaska will yield an extraordinary scientific impact. Some 132 PBO GPS stations in Alaska have been operating for over five years, yielding precise time series, and thus useful constraints on regional surface deformation. In 2013 the USArray Transportable Array (TA) will begin to deploy a grid of ~290 stations across Alaska and into parts of Canada–each site equipped with broadband seismometers, infrasonic sensors, and (at some sites) strong motion accelerometers. Alaska promises to produce a rich data set given that it has: a seismicity rate five times higher than the lower 48 states combined; a complex crustal history; continental-scale fault systems; and significant surface motion everywhere relative to stable North America. Further, there is a high likelihood of recording a magnitude 7 or larger earthquake during any five-year time window and any major volcanic activity has a reasonable chance of being captured simultaneously by the PBO GPS network and the TA seismic and infrasound network.

The 2011 EarthScope workshop report *Opportunities for EarthScope Science in Alaska In Anticipation of USArray* (Freymueller et al., 2011a) highlighted the pan-EarthScope science opportunities in Alaska. As the report notes, "In many ways Alaska is a geoscience frontier with enormous area never having been studied beyond reconnaissance level." The reports highlights a number of globally relevant science topics that will be addressed by EarthScope in Alaska, including subduction processes, mantle flow, terrane accretion, far-field deformation, and glacial unloading. That the Alaskan subduction zone is capable of producing great earthquakes and devastating tsunamis heightens the societal relevance of the research. Taken together, the scale and scientific opportunities in Alaska make it an ideal target for EarthScope and more than justify the enormous operational challenges associated with deploying and maintaining stations there.



Earthscope in Alaska, showing PBO GPS stations (yellow symbols), the proposed USArray Transportable Array deployment (red symbols) and existing real-time seismic stations (blue symbols).

- Clear evidence for extremely low friction coefficients on fault rocks sampled by SAFOD, confirming that the fault slips under very low shear stresses.
- Integration of accelerometer records with GPS data for characterizing earthquakes, advancing GPS-seismology and early warning systems.
- Direct three-dimensional mapping of crustal deformation patterns and mountain uplift in the western US.
- Unprecedented seismic imagery of the structure of the crust and mantle that underlies the western US, revealing the fate of more than 100 million years of Farallon plate subduction.
- New seismic images of the lithosphere asthenosphere boundary, mantle transition zone and structures that provide a record of western US tectonomagmatic history.
- New constraints on the location and geometry of lithospheric instabilities that influence the dynamics of western US deformation.
- Insights into mechanisms of Great Basin deformation that accommodate gravitational collapse of the continental interior.
- New seismic constraints on deep mantle dynamics, core-mantle boundary, and core structure.

Building on EarthScope Success: 2013–2018

In October 2009 the EarthScope community met in Snowbird, Utah to discuss science goals, to plan for the future of the program, and to clearly articulate its underlying scientific priorities. The report from that meeting, *Unlocking the Secrets of the North American Continent: An EarthScope Science Plan for 2010–2020* (Williams et al., 2010) charts the state and direction for EarthScope science.

This proposal describes the status and direction of EarthScope science, providing an update to topics in the Science Plan, and includes additional topics that have come to the fore since 2009. Because of the breadth of disciplines and development of technologies that comprise EarthScope research, sustained efforts and unique opportunities continue to advance the sciences of Earth observation, modeling, integration, interpretation and dissemination of results.

Over the next 5 years, the EarthScope Facility, will continue to support and advance this community science plan. Specific tasks outlined in this proposal include:

- Growing the EarthScope community. Support for workshops, institutes, community involvement, education and outreach efforts, and governance will be essential to maintain this element.
- Expanding EarthScope's geographic focus. Completion of observations by the Transportable Array to the Eastern margin of North America, the expansion of the TA to Alaska and the continuation and augmentation of Plate Boundary Observatory observations will focus regional activities and opportunities for partnerships with other communities and programs such as GeoPRISMS.

- Strengthening data analysis, integration, and interpretation. Continued development of data products and cyberinfrastructure will be guided by the recent report *A Preliminary Strategic Plan for EarthScope Cyberinfrastructure* (Gurnis et al., 2012). Open access to higher-level data products that build on the expertise of community members will provide information that is easily accessible to an increased number of users.

EarthScope Beyond 2018

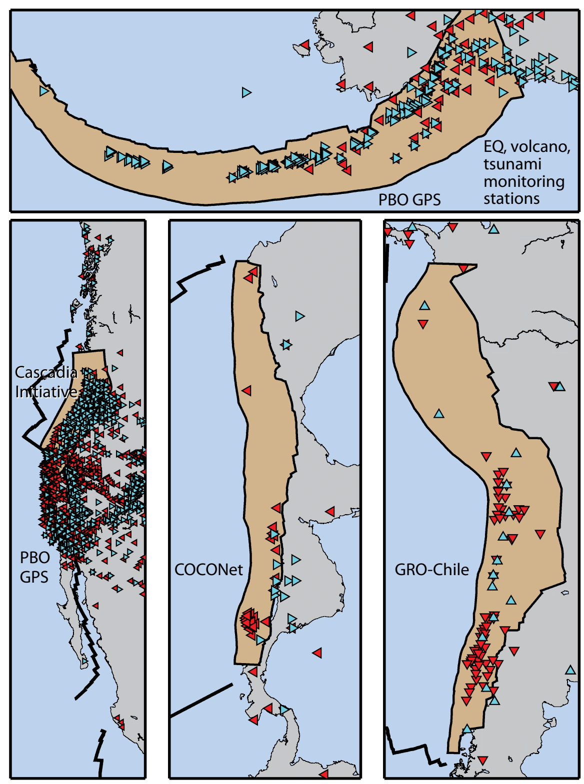
EarthScope has become the global standard for a broad-based, community-driven, integrative research facility that provides a nexus for interdisciplinary science. The Earth system processes of relevance to the EarthScope scientific community operate on time scales longer than the originally planned 15-year lifespan of the facility, and we expect that a legacy of EarthScope observing systems will continue to sample time-varying phenomena beyond the 2018 horizon. Tectonic deformation is a predominately slow process, and commonly does not occur in a steady state. Earthquake cycle deformations, which are both subject to and offer insight into the rheology of the Earth, can vary over decades to centuries. Just as new and unexpected mechanisms of plate boundary deformation such as ETS were discovered when precise geodetic observations became available at interannual periods, and were better understood in light of high resolution seismic mapping, additional new, interesting, and important modes of deformation related to hydrogeodesy are revealed as interdecadal records become available. In addition, managing, mining, visualizing, and integrating very large, disparate datasets are now coming of age with enhanced cyberinfrastructure, driven by such new initiatives such as *EarthCube* at NSF and *COOPEUS* in Europe.

Beyond 2018: A Subduction Zone Observatory?

The success, knowledge, and experience of EarthScope provide an unprecedented launching point for IRIS and UNAVCO to collaborate on the creation of a planetary-scale Subduction Zone Observatory (SZO). This observatory, stretching 18,000 km along the eastern Pacific Ocean, from the Aleutians in the north, to the tip of Tierra del Fuego in the south, will provide an integrated, interdisciplinary approach to understanding the entire subduction zone as a system. SZO research will have enormous societal relevance, given the population centers all along the coast that are subject to earthquake-, tsunami-, and volcano-related hazards.

Existing geophysical networks and observatories will provide the SZO's starting backbone (see Figure). The Plate Boundary Observatory (PBO) core—the set of GNSS sites that will form the post-EarthScope backbone in North America—will be one among an anticipated federation of geodetic networks that will overlap with new SZO. Current NSF-funded IRIS and UNAVCO activities, such as the GRO-Chile seismic network, the COCONet GPS network, and the onshore and offshore stations of the Cascadia Initiative will provide key infrastructure. The SZO will grow through infill with strategic deployments of broadband seismometers and high-sample-rate GPS. Small, flexible PI-led projects can be designed and performed within this larger framework.

An SZO will be a major international initiative, and IRIS and UNAVCO propose to begin now to collaborate on bringing together the necessary geographic, organizational, and disciplinary representation to develop the SZO concept and articulate the science benefits.



The SZO, showing locations of present GPS (red) and seismic (blue) stations that report data in near-real time. (top) Aleutians-Alaska Peninsula. (left) US-Canada west coast. (center) Central America. (right) South America. The brown shading indicates the lateral extent of the seismogenic portions of subducting slabs, illustrating the tremendous variability in subduction processes and other plate boundaries along the length of the SZO. At present, the availability of observations along the SZO varies widely.

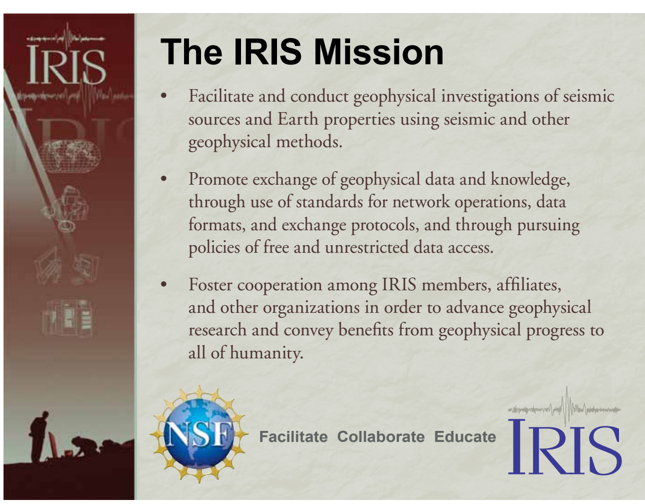
Governance and Management

The Consortium and Its Goals

IRIS was formed in 1984 by the US academic seismology research community to define and prioritize the community's facility needs to support their expanding research efforts, and to seek support from NSF to establish, develop, and operate these facilities. Incorporation as a 501c3 not-for-profit allowed IRIS to create the business and financial structures needed to receive and manage federal funds through Cooperative Agreements and other awards from NSF, on behalf of Consortium members. For the more than 25 years since its inception, IRIS has developed and grown the facilities that are now central to the Earth science research and education communities in seismology and related fields. Consortium membership has increased from the 27 original member institutions to 116 today. Recognizing the importance of educational and international outreach and cooperation, membership now includes 21 Educational and 116 Foreign Affiliates.

The 1984 founding proposal for IRIS identified a 10-year program to implement four national facilities for seismology, including "a Global Digital Seismic Array with real-time satellite telemetry from 100 observatories, a 1,000-unit portable digital seismograph Mobile Array, central data management and distribution facilities to provide rapid and convenient access to data for the entire research community, and a major computational facility capable of supporting analyses of the new data."

Today, the original IRIS goals for instrumentation and data management have been surpassed and new technologies and facility resources, unforeseen in the mid-1980s, have been incorporated. Community direction has provided the basis and motivation for the refinement and support of IRIS development of these forward-looking facilities and services.



The Board of Directors, the program standing committees, and other IRIS governing bodies all comprise active researchers who themselves carry out cutting-edge research and publish their results, and participate in dozens of scientific conferences, workshops, and review panels in the United States and around the world. The strength and validity of the Consortium depends on sustaining and adapting facilities to enhance these research opportunities, and relies on the continuous input of this research community. The ongoing support of any facility program requires a delicate balance among operating, maintaining, and refurbishing existing facilities, and investing in both technological innovation and new initiatives that advance the science. IRIS is committed to continue to support and maintain those core facilities and resources that form the essential underpinning for a broad sector of research support for the US academic community. At the same time, we seek to provide the infrastructure and facilities to support the research community in new and interdisciplinary lines of research in the Earth sciences.

Achieving the IRIS goals has involved diversifying funding bases, collaboratively working with other agencies besides NSF to develop and sustain the facilities, and working with hundreds of international partners to provide the global coverage and communications facilities that underlie the facilities. NSF can legitimately view its investment in IRIS facilities as being heavily leveraged to the benefit of the scientific undertakings of the seismological research community.

The ultimate success of IRIS must be gauged by the scientific impact of the facilities. Open access to IRIS data and instruments has enfranchised seismological research programs at a large number of US universities, and these open data policies also have established a precedent for international sharing of many varieties of scientific data. The hundreds of peer-reviewed research papers published each year that are based on the use of IRIS facilities provide strong testimony to the importance of IRIS resources in enabling research (Figure Gov-1).

IRIS Governance and Management

The IRIS governance and management structure is the interface between the scientific community, funding agencies, and IRIS programs. The structure is designed to ensure close involvement of the research community in the development of IRIS facilities, to focus scientific talent on common objectives, to encourage broad participation, and to effectively manage IRIS programs. Community involvement in IRIS governance and management has been a key to the Consortium's success. Each year, over 80 scientists from more than 50 research institutions participate in the governance and management of IRIS through its Board of Directors, committees, and advisory groups.

As a ***consortium of research universities***, IRIS members provide advice and direction on IRIS activities. Through ongoing interactions with scientists at member institutions and through formal structures such as workshops, annual meetings, symposia, and newsletters, the research community interacts with IRIS and, through the Consortium, expresses its evolving needs to funding agencies. The enthusiasm and experience of its members guide IRIS in how it supports Earth science and encourages cutting-edge research.

As a ***major facilities program*** for NSF, IRIS works closely with the NSF Division of Earth Sciences to develop programs focused on the support of facilities on which NSF-funded seismological research is based. Through a series of Cooperative Agreements, NSF has provided funding with which IRIS, on behalf of the research community, operates and manages the GSN, PASSCAL, DMS, EPO, and EarthScope's USArray. In recent years, funding supplements have been provided by the NSF Office of Polar Programs and the Major Research Instrumentation program to develop and acquire special purpose instruments for use in polar regions. In 2011, an Ocean Bottom Seismograph Instrument Pool (OBSIP) Management Office was established, with funding from NSF's Division of Ocean Sciences, for IRIS to coordinate the OBSIP. Because many operational aspects of the IRIS programs are closely integrated with activities at the USGS and other federal and international programs, joint IRIS/NSF coordination on interagency and intergovernmental activities is also essential to maintaining effective programs. Other federal agency support has included funds for the acquisition of portable and permanent station instrumentation by the Departments of Energy and State.

As a ***corporation***, IRIS provides the legal and fiscal structure through which NSF and other funding agencies can interact with IRIS for the stable operation of its facilities, and a mechanism for developing programs and bringing the wishes of its members to fruition. Through its professional staff, committees, and subawardees, IRIS provides continuity in institutional and personnel resources for operational and developmental activities.

Consortium Membership

IRIS bylaws specify that educational and not-for-profit institutions chartered in the United States with a major commitment to research in seismology and related fields may become Members of IRIS. Two- and four-year colleges and universities with a commitment to teaching Earth science, including seismology, may become Educational Affiliates. Research institutions and other not-for-profit organizations both inside and outside the United States engaged in seismological research and development that do not otherwise qualify for IRIS membership, may be elected Affiliates or Foreign Affiliates.

In June 2004, the IRIS membership modified the bylaws to transition from a structure in which all member institutions held seats on the Board of Directors to one in which a nine-member Board of Directors elected by representatives of Member Institutions executes the executive powers of the corporation. Under this new structure, Member Institutions retain significant powers, including voting to revise the bylaws, electing Board members, and calling special meetings. The Board of Directors meets in person three times per year, and holds frequent conference calls, to receive reports of programmatic activities, guide the development of ongoing programs and new activities, approve annual program plans and budgets, appoint members to supporting committees, monitor the fiscal state of the corporation, participate in the development and review of new proposals, and transact other activities that require Board action. The annual meeting of the full membership takes place in December during the American Geophysical Meeting in San Francisco. Consortium activities also take place at the annual IRIS or EarthScope Workshops (held in alternating years, most recently an IRIS Workshop in Boise, ID, June 2012), where scientific sessions, technical training, and small group discussions provide an opportunity for the seismological community to learn of IRIS and EarthScope activities and resources, and to provide input to the development of future plans.

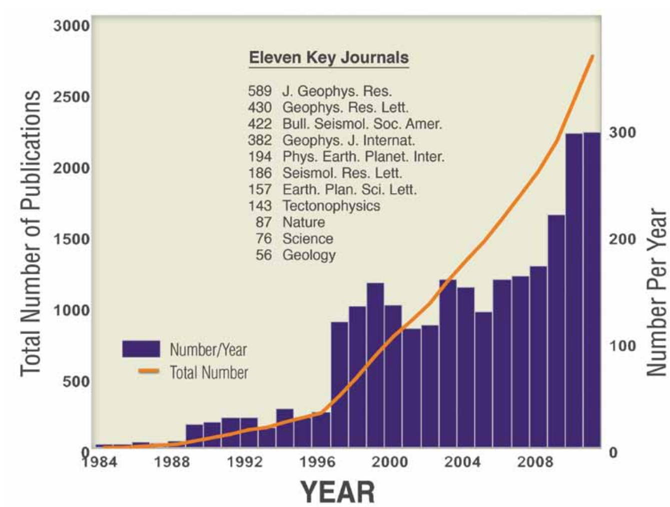


Figure Gov-1. IRIS maintains a bibliography of IRIS-related publications that has been developed through submission of citations by authors and through a detailed search of key journals. Annual searches through the contents of the eleven key journals listed in the figure have been used consistently since 1984 to identify articles that reference IRIS or use data from IRIS-related programs. More than 2700 peer-reviewed articles have appeared in these journals, 1984–2011 (total number per journal are indicated). Four stages are apparent in the growth of publications. Early articles (1984–1987) dealt with descriptions of the nascent Consortium. Early PASSCAL experiments and limited GSN data were the basis for a moderate increase in publications (1988–1995). In 1995, significant expansion of the GSN, completion of a number of PASSCAL experiments, and initiation of the DMS archive resulted in a large increase in the rate of publications. With the start of EarthScope, and the emergence of Transportable Array data, the rate increased significantly between 2008 and 2010. The full IRIS bibliography contains more than 4800 articles. These long-term trends in increasing publication rate are evidence of the value of NSF's decadal investments in the collection and preservation of Earth science data.

Governance

The nine-member IRIS Board of Directors acts on behalf of the Member Institutions, and serves as the major decision-making forum for IRIS in guiding the programmatic, management, and fiscal activities of the Corporation and Consortium. It sets goals and policies, reviews and approves program plans and budgets, receives advice from Board-appointed committees, and directs the activities of the President and staff. The IRIS bylaws stipulate "the Board of Directors may designate one or more standing committees for each major scientific, educational, or research program to which the Corporation provides scientific counsel and advice or management direction." In addition, the President and the Board of Directors can appoint special advisory committees and ad hoc working groups. It is the role of all appointed committees to develop recommendations for the Board, which in turn, evaluates and acts upon such recommendations on behalf of the Member Institutions.

The Board of Directors has three subcommittees drawn from Board membership—Budget and Finance, Membership, and Legal Affairs—that are responsible for coordination of key Board functions. The Board also appoints membership to the Nominations Committee to prepare a slate for the annual election. A Program Coordination Committee is led by the Board vice-Chair and includes a second Board representative, standing committee chairs, and program managers. It integrates activities that crosscut the individual programs and is charged with developing a coordinated program budget each year for presentation to the Board. The chairs of all Board-level committees participate in Board meetings on a nonvoting basis.

Special joint committees have been established to provide oversight to IRIS programmatic activities that intersect with other organizations. The Polar Networks Science Committee is a joint committee with UNAVCO to guide development of geophysical facilities in the Arctic and Antarctic. An OBSIP Oversight Committee has been formed recently to guide new IRIS responsibilities in managing national facilities for ocean bottom seismic observations. The GSN Standing Committee plays a special role in coordinating activities and providing advice to the USGS Earthquake Hazards Program.

Currently, standing committees represent each of the core IRIS programs (GSN, PASSCAL, DMS, and EPO), and a USArray Advisory Committee (formed in 2003) provides advice and coordination of the special USArray activities and their intersection with the core programs. With the recent Board-sanctioned reorganization of the IRIS management structure (described below), and the integration of the core and USArray programs presented in this proposal, the Board is in the process of developing adjustments to the governance structure that will streamline the interface among the Board, programs, and management, in parallel with the new management organization under Instrumentation Services, Data Services, and EPO. In its is deliberations, the Board is giving careful consideration to simplifying the governance structure and reducing the number (and expense) of committee meetings, while at the same time maintaining the essential engagement and direct input of the community through their participation on committees and working groups. These adjustments will be finalized over the next year, during ongoing consultation with the community membership, IRIS management, NSF, and other stakeholders, and implemented with the start of the anticipated new Cooperative Agreement in October 2013.

One of the greatest strengths of IRIS continues to be the strong engagement of a broad sector of the scientific community in the governance and management of the Consortium and facilities. Membership on the Board of Directors is restricted to individuals from Consortium Member Institutions, but the standing committees, other committees, and working groups can draw from any institution. Indeed, a number of scientists from government agencies and labs participate, enriching the input to the committees and enhancing interagency collaboration. While a number of committed individuals have been exemplary in their dedication through continued service over the years, often on multiple committees, there has also been an explicit effort to engage new committee members, especially younger scientists. This process of engagement and refreshment in governance is an important part of sustaining many of the underlying goals of IRIS and the principles under which the Consortium operates, such as the culture of open data sharing. The constant feedback and advice from a community of active scientists has been essential to the success and evolution of the programs and facilities operated by IRIS.

Management Structure

IRIS facility management is based on linked operational structures for the main programmatic areas—Instrumentation Services (GSN, Portable Seismology, USArray, Polar Support Services, and OBSIP), Data Services, and EPO. The central administrative and business functions are carried out through a Headquarters Office in Washington, DC. The programs are managed through offices or subawards linked to each of the programs. Overall management is under the direction of a full-time President, appointed by the Board, who works with a Senior Management Team that includes the directors of each of the primary program directorates (Instrumentation Services, Data Services, and Education and Public Outreach), Director of Program Support and Special Projects, and Chief Financial Officer.

Each IRIS program operates under a standardized management and oversight structure (program manager and advisory committee) and is implemented through a combination of direct employees, subawards, and partnerships that varies depending on the requirements of the individual program. USArray has had a parallel management and oversight structure consisting of a director and advisory committee. Additional oversight and management of USArray, as part of the EarthScope Program, has been provided by NSF, through an EarthScope Management Team (with representatives from NSF, IRIS, and UNAVCO) and the EarthScope Science Steering Committee (closely linked to the EarthScope National Office, currently operated through Arizona State University).

To establish more integration between programs, IRIS management was restructured in 2010 to build on synergies between the core programs and USArray. The most significant high-level change integrates the key technical activities of IRIS under three primary elements: Instrumentation Services, Data Services, and Education and Public Outreach (Figure Gov-2):

- ***Instrumentation Services***: Enhances coordination of technical activities, field programs, and development efforts involving GSN, PASSCAL, USArray, and related activities in Polar Support Services and OBSIP, while retaining the individual identities and disciplinary support for portable and permanent observations.
- ***Data Services***: Focuses the strengths of existing DMS activities and enhances user-centric, data-related services, quality control, and products.
- ***Education and Public Outreach***: Takes an expanded role in bringing the activities of IRIS and the seismology community to the public and the educational arenas. These efforts will be enhanced to coordinate pan-IRIS efforts in training, especially in collaboration with International Development Seismology, and documentation of best practices.

These changes improve IRIS services by encouraging more interaction among programs and opening up new initiatives, especially in instrumentation, enhanced data services, international engagement, and polar programs.

Full-time staff devoted to IRIS activities are located at the Data Management Center in Seattle, Washington, the PASSCAL Instrument Center in Socorro, New Mexico, the IDA/GSN and Array Network Facility groups at UC San Diego in California, and IRIS Headquarters in Washington, DC. There is the equivalent of approximately 135 full-time staff involved in the operation of IRIS facilities and IRIS-related programs: 60 full-time employees are on the IRIS payroll, and an approximately 75 more full-time equivalents are supported through major IRIS subawards. The USGS facility in Albuquerque, New Mexico, provides significant dedicated support for the GSN, but is separately funded by the USGS.

IRIS Business Office (Financial Services and Sponsored Projects) at IRIS Headquarters is responsible for accounting and financial controls, contracts and awards, procurement, inventory, insurance, management policies and procedures, proposal submission, and reporting.

Program Development and Review

The primary instrument for IRIS support has been a series of five-year Cooperative Agreements between IRIS and NSF. These awards are based on proposals that review the current state of the facility and outline the goals for activities for the next five years. Separate five-year awards have been used to support the core programs (through NSF EAR Instrumentation and Facilities Program) and EarthScope/USArray, with other, smaller awards to support Polar Support Services and part of the EPO activities. The Board of Directors approves all IRIS proposals and annual program plans and budgets, after development through a systematic process designed to distill the collective scientific interests and priorities of over 100 member research institutions. In addition to the five-year cycle of reviews carried out as part of the NSF proposal process, the IRIS management structure, and the organization within specific programs, have also been periodically reviewed and evaluated by internal and external committees. A Business Systems Review by the NSF Large Facilities Office and a series of audits by the NSF Office of Inspector General were recently completed and reported favorably on IRIS management and business practices. The mode of NSF funding for the IRIS facilities—five-year Cooperative Agreements with annual program plans and budgets—has provided a level of both stability and flexibility that has allowed the facility resources to

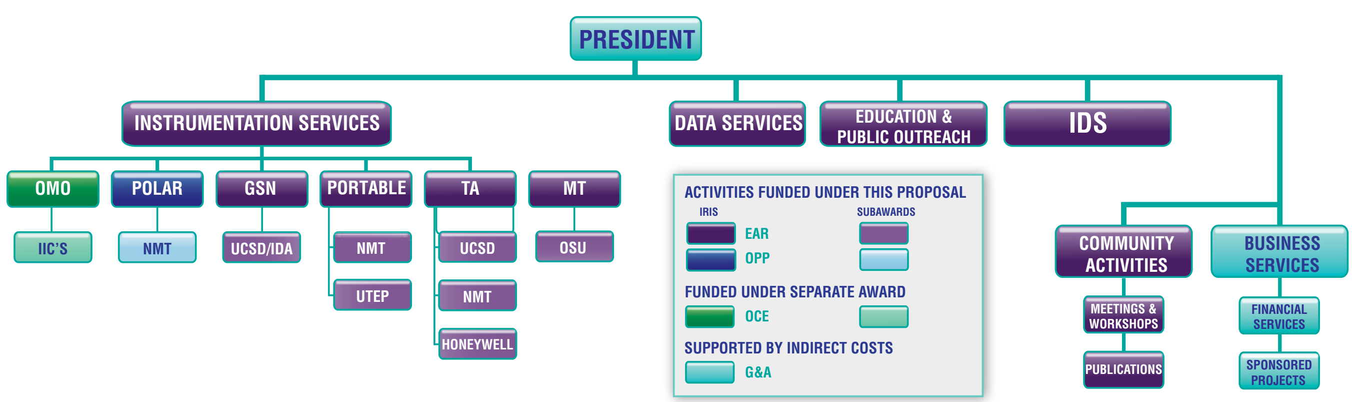


Figure Gov-2. The IRIS management structure was reorganized in 2010 under three service areas, a pan-IRIS activity in International Development Seismology (IDS) and Community Activities. Data Services and Education and Public Outreach activities are carried out primarily by IRIS staff with minor subawards. Instrumentation Services consolidates all IRIS instrumentation programs and includes a number of major subawards as shown in the figure. Support for Polar activities is requested in this proposal under separate funding provided by the NSF Office of Polar Programs. Funding for all other activities except OMO (OBSIP Management Office) is requested in this proposal. Acronyms are explained in the glossary at the end of this section of the proposal.

evolve in response to changing scientific needs and technical developments. Under this proposal for a new five-year (2013–18) Cooperative Agreement to integrate the core programs with USArray, it is anticipated that this tradition of close coordination between NSF and IRIS will continue and that interactions with UNAVCO will increase, as overall program goals and plans are established and annual budgets and tasks are set.

The IRIS programs have also made ongoing adjustments to respond to international developments. As hardware and data procedures established by IRIS have become de facto standards, there have been increasing opportunities for international collaboration in areas such as station installation, data exchange, and field experiments. In this proposal, we place increasing emphasis on extending these standards to include metrics and procedures for assessing data quality, so as to leverage the utility of data that accrue from significant international investments in new observational technologies. Through the evolving IRIS program in International Development Seismology, we will also significantly improve and formalize IRIS investments in documenting best practices in observational seismology, data management, and education, to enhance the quality of growing international investments in national and regional earthquake monitoring networks and to encourage regional and global data exchange.

In all of these areas, decisions to adjust facility priorities have been directed by the advisory committees and Board of Directors, based on consideration of their scientific and technical merits.

Collaborations and Partnerships

IRIS has entered into partnerships with both national and international agencies and groups whose scientific goals overlap those of IRIS. These partnerships range from formal documents and Memoranda of Understanding to "a handshake," illustrating the flexibility with which IRIS can act in serving and furthering its scientific programs. In addition to various modes of interaction with Consortium Member Institutions, some of the principal organizations with which IRIS interacts in the United States include: the USGS, the Southern California Earthquake Center, the USGS Advanced National Seismic System (and many of the associated regional networks), the Global Centroid Moment Tensor group at Lamont, UNAVCO, the Network for Earthquake Engineering Simulation (NEES), GEON, Computational Infrastructure for Geodynamics, Cooperative Institute for Deep Earth Research, the UNIDATA program center of the University Consortium for Atmospheric Research, the American Association of State Geologists, the National Aeronautics and Space Administration Jet Propulsion Laboratory, DOE and its labs, and the Air Force Technical Applications Center.

As partners in the operation of the EarthScope facility, coordination between IRIS and UNAVCO has increased over the past 10 years and close interactions will continue to be strengthened over the next five years. In addition to technical aspects of station operations and siting for PBO and USArray, there are a variety of related joint activities between IRIS and UNAVCO, especially in Education and Public Outreach, Data Services, and Polar Support Services, which are discussed in later sections of this proposal. Other key collaborations with US academic organizations that link to the EarthScope program are established interactions with the EarthScope National Office and various cyberinfrastructure initiatives, including Computational Infrastructure for Geodynamics and the EarthScope Cyberinfrastructure subcommittee, and exploratory interactions with supercomputer facilities supported by NSF and DOE.

Among its US agency partners, IRIS has formed its strongest ties with the USGS. The USGS presence and stability have proven to be of great importance throughout the IRIS programs. The USGS (through it Albuquerque Seismological Laboratory [ASL]) has been a partner with IRIS in the GSN since its inception. The ASL group is responsible for operation of more than 60% of the GSN stations. There has also been close collaboration among IRIS, EarthScope, and the USGS related to the USGS Advanced National Seismic System and its proposed enhancements using Transportable Array stations in the central and eastern United States.

Collaborations with many international organizations have been essential to the health of IRIS as a global observing program. Each of the more than 100 GSN stations outside the United States represents some level of formal international partnership developed by IRIS and the USGS. These partnerships range from large and complex agreements with China, Russia, and many of the states of the former Soviet Union, to arrangements with national universities or geological surveys, to operating agreements with private organizations and individuals. Collaborative projects, many of them initiated by IRIS or resulting from university research programs using PASSCAL instruments, have made it possible to install modern seismic stations and gather first-class data from regions of the world that were inaccessible to seismologists 25 years ago. GSN stations play an important role in the International Monitoring System for the Comprehensive Test Ban Treaty Organization. These and other partnerships provide an extremely cost-effective mechanism to operate a global facility, and provide an avenue for US researchers to work in regions of the world that otherwise would be difficult to access. Many PASSCAL experiments have been able to build on contacts that have emerged though IRIS interactions with foreign institutions. Conversely, many of the IRIS Foreign Affiliates have joined as the result of interest in IRIS and its programs developed though contacts made during GSN installations or PASSCAL-supported experiments. The IRIS activities in International Development Seismology seek to leverage these opportunities to assist developing nations in their efforts to establish modern earthquake monitoring systems and to enhance the opportunities for US researchers to engage with foreign partners in both research and training.

Facility Description and Activities

This proposal comes at a critical phase in the evolution of seismological research and IRIS. Maintaining a facility for research in seismology requires constant attention to the balance between sustaining high-quality, stable observations for tracking long-term changes in earthquake activity, and nurturing innovative technologies for expanding the observational base and exploring newly discovered aspects of Earth structure and the way in which the planet deforms. The original IRIS goals for instrumentation and data management have been met and surpassed and new technologies and facility resources, unforeseen in the mid-1980s, have been incorporated. As shown in previous sections of this proposal, research based on the existing facilities has revolutionized our understanding of many aspects of Earth structure and the processes that control earthquake rupture. With the merging of the original IRIS core programs and USArray, we have an opportunity to consolidate and streamline operations to sustain the current base and respond with a limited number of evolutionary new initiatives in response to the community's constant stimulation to move in new and innovative directions. The following sections of the proposal describe the ways in which we intend to continue to mange each of the key elements of the IRIS facilities to achieve that balance between sustaining the core and innovating for the future.

Current Facility Status

The Global Seismographic Network is a globally distributed, state-of-the-art network of more than 153 stations sustained by a close partnership between NSF, the USGS, and many international partners. With the merging of PASSCAL and the USArray Flexible Array, Portable Seismology now includes more than 1300 three-component and 2500 single-channel instruments that are loaned to researchers funded by NSF and other agencies and used worldwide in more than 70 experiments per year. The USArray Transportable Array is completing observations at a total of more than 1600 sites in an unprecedented traverse across the conterminous United States, and it is preparing to transition to Alaska. IRIS Data Services provides open and easy access to all IRIS data holdings and data products, along with even larger quantities of contributed data and virtual pathways to international data archives. There are approximately 170 terabytes of data archived in the Data Management Center, and more than 300 terabytes are expected to be shipped to researchers in 2012. With these facilities today, in the wake of a large global earthquake, any researcher can retrieve seismic waveform data in real time from over 2000 seismic stations around the world via the Internet.

Education and outreach activities are integrated across all IRIS programs. The IRIS website receives over six million unique visitors annually and the majority of these visits are to nonspecialist pages. IRIS Education and Public Outreach has developed a variety of activities to motivate and prepare future Earth scientists, including a very successful internship program that has paired 129 undergraduates with researchers across the United States for summer projects. A remarkable 90% of IRIS Intern alumni who have completed their undergraduate degree have gone on to graduate school and careers in the geosciences. A number of these interns have been instrumental in establishing a cadre of Early Career Investigators who are working with IRIS to develop a suite of special services (website, blog, teaching materials, speaker series, mentoring service) of interest to postdocs and pretenure faculty. Over 114 students from 47 universities have taken a primary role in identifying sites for USArray Transportable Array stations. Twenty-one scientists have given over 115 public lectures at museums and education institutions across the country as IRIS/SSA Distinguished Lecturers. Over 1200 teachers and college faculty have attended one-day or longer IRIS teacher training workshops.

IRIS programs have articulated new goals with each succeeding five-year proposal, many of them in support of training and outreach objectives. Data Services has supported international metadata workshops on data formats and digital network functions. Portable Seismology provides extensive training to ensure the adoption of best practices in field experiments and data collection. EPO has grown to become one of the most successful of NSF's solid Earth science outreach efforts. Over the past ten years, the NSF Office of Polar Programs has supported IRIS activities in polar regions, including development of specialized cold-region instrumentation and enhancements to observational techniques and data recovery, especially for experiments in Antarctica. In 2011, the Division of Ocean Sciences began funding IRIS to establish the OBSIP Management Office to coordinate activities at three national facilities for instrumentation in ocean bottom seismology. All of these new activities have been carefully reviewed and vetted through workshops, committee deliberations and Board actions, before being adopted to strengthen and enhance the core IRIS programs.

Proposal Themes

Underlying the specific activities and goals presented in the remainder of this proposal are the following general themes that have guided the Board's development of the proposed plan and that underlie the IRIS approach to serving the facility needs of the US academic research community:

- ***Establishing quality standards.*** A key step in the early development of IRIS facilities was the definition of technical specifications for a new generation of observational systems and data exchange formats. This investment in careful design, coupled with an active encouragement of the adoption of standards and open access to data, led to the significant improvements and uniformity in instrumentation in networks throughout the world. In this proposal, we describe activities that will place increased emphasis on the improvement, assessment and documentation of data *quality*. While the instrumentation may be similar in various networks throughout the world, there remain significant differences between networks in terms of operational practices, the quality of data collected and the modes of data access and distribution. Through the development and documentation of standardized procedures for station installation, data management, and quality assessment—coupled with training and the adoption of appropriate standards and metrics—we have the opportunity to leverage significant improvements in the value of data collected for research and hazard mitigation throughout the world. Documentation of IRIS policies and procedures will be an important part of this effort and this proposal includes requests to make the necessary investments, across all IRIS services, to develop and disseminate information describing our experience and "best practices."
- ***Developing synergy.*** The reorganization of the IRIS management structure in 2010 brought all of the IRIS observational programs under Instrumentation Services and simplified the interactions with Data Services and Education and Public Outreach. Over the past two years, and especially during the development of this proposal, it has become clear that this enhanced structure has great value in encouraging interactions between programs and implementing technical and organizational solutions. The IRIS Board is actively exploring changes to its governance structure to further strengthen this pan-IRIS approach with the goal of increased communication, enhanced responsiveness to the research community, and more effective use of resources.
- ***Creating efficiency.*** IRIS seeks to operate all facilities efficiently, with continuous feedback and guidance from the governance structures to ensure programs are applying resources to optimize the science return. In the current proposal, this is particularly important as IRIS' USArray and traditional core activities are fully integrated within a single funding structure. Operationally, these activities have been closely integrated since the initiation of EarthScope. USArray Flexible Array activities have always been integrated with the PASSCAL Instrument Center operational and management structures, similarly, for USArray Data Management and Siting Outreach activities. These integrated activities have realized substantial operational and cost efficiencies since the inception of EarthScope and have avoided the creation of redundancies in facilities or management. With this proposal we ensure the integration is complete and holistic throughout management, governance, subawards, new activities, and planning.
- ***Sustaining NSF investments.*** Stable and continuous support from NSF for facilities and research has placed the US academic community at the forefront of global research in seismology. To continue that leadership requires constant vigilance and ongoing investments to ensure that the national infrastructure is sustained and the research community remains stimulated and engaged in forward-looking exploration and discovery. This proposal seeks to sustain the core investments, though careful stewardship of the current investments in instrumentation, data, and educational resources, while making limited investments in new technologies as the basis for a future facility that remain vital and responsive to scientific needs.
- ***Encouraging international activities and collaborations.*** Collaboration has long been an essential component of seismology as a global and international science. International partnerships with foreign research and government organizations have been critical in operating the GSN and DMS and, through Principal Investigator activities, in mounting PASSCAL projects throughout the world. IRIS recently established a program in International Development Seismology to assist in the development of the technical resources for earthquake hazard investigations in hazard-prone areas of the developing world and to encourage partnerships with US academic institutions in training and the development of joint research programs. In addition to responding to societal needs in building a safer and more resilient world, these activities can contribute to fundamental research interests through enhanced observational systems and access to improved data.
- ***Nurturing community engagement.*** IRIS relies on the pro bono leadership provided by community members engaged in IRIS governance as a founding strength of the Consortium. Outreach through our website, publications, annual IRIS and EarthScope meetings, and special workshops allows the broad community to remain informed and engaged in development and use of IRIS multi-user facilities. A key element in building for a productive future is to invest resources to engage and sustain the next generation. Through our EPO programs we reach out to students to stimulate their interests in the Earth sciences. Through the proactive engagement of Early Career Investigators, and the participation of young scientists in our standing committees, we encourage the next generation to be directly engaged in defining the future of their Consortium and its programs. As a Consortium representing the US academic research community in seismology, the primary mission of IRIS is to enable the success of that community's research endeavors through activities that are only possible through a national facility.

3.1. INSTRUMENTATION SERVICES

A wide range of seismological research depends critically on carefully made instrumental observations. This is true whether the target is Earth's core, continental-scale structure, or shallow sediments at Earth's surface. This is true whether using signals of thousands of seconds period (to study Earth's free oscillations, mega-earthquakes, and the response to tidal forcing); or signals of tens to thousands of Hertz (for high-resolution structural mapping and near-source studies). This is true whether making observations of a few seconds duration (to capture an active-source explosion); or decadal-scale observations (to capture the evolution of subduction zones and even global climate). IRIS Instrumentation Services (IS) provides the infrastructure for these observations, whether by deploying and operating stations, making sensors available to others, setting and promoting global standards, or guiding the development of new observational technologies. Further, IS ensures these varied efforts are coordinated and efficient, best practices are identified, implemented, and documented, and knowledge is shared toward the common goal of enhancing capability, quality, and cost performance of observational seismology.

Historically, specific programs within IRIS were designed to address targeted observations that required unique equipment or characteristics. For example, GSN (in collaboration with the USGS) makes exquisite decadal-scale ultra-long-period observations via instruments installed in carefully constructed vaults and boreholes, while PASSCAL enables PIs to take ruggedized station kits to the farthest reaches of the planet for temporary deployments. The Polar Support Services program creates cold-hardened systems that are deployed quickly during short field seasons, while the USArray Transportable Array (TA) has developed processes to efficiently migrate a 400-station array in year-round operations. However, with advances in technology, the different IRIS instrumentation programs and activities are now very similar in instrumentation and approach. For example, the GSN uses the same data loggers and (secondary) sensors as the TA—enabling common approaches to the management of these units. Several sensor models are common to all IRIS programs—allowing IRIS to work with vendors to drive development and negotiate favorable prices and delivery schedules. Common strategies for sensor emplacement and orientation to optimize cost and performance are being pursued—the TA, GSN, and the USGS have recently created a testbed for evaluating sensor performance in low-cost "posthole" type installations (Figure IS-2). As all of these technologies and procedures evolve, the IS structure ensures that the multiple IRIS observing programs share knowledge and effort in pursuit of common goals.

Figure IS-1. Instrumentation Services supports activities in a wide range of environments, from polar to equatorial, with installations ranging from permanent to highly temporary.

The IS management structure has continued to evolve since it was established two years ago as a first step in moving toward NSF's stated desire for IRIS to merge management of the original core programs and USArray. Although numerous technologies and technical concerns bind IS together, it has evolved into more than just technical interchange. IS is an approach and a collaboration that is focused on best practices—both technical and management. A number of important best practices have been put in place over the past two years, and they provide the roadmap for the future.

IS implementation of ***best practices in project management*** includes the use of procedures to better define and prioritize new projects. For example, Project Charters (a well-defined structure in project management) are used to define nascent projects in a structured way that identifies benefits and stakeholders, avoids redundancy, and communicates objectives across programs. Having clearly defined project goals and benefits focuses our efforts on those projects that deliver the greatest return, and ensures these projects deliver benefits to multiple programs. Current projects managed in this way range from the large and exciting, such as sensor emplacement testing, that will, over time, impact how scores of experiments deploy thousands of sensors, to the small and mundane, such as developing a new $20 test jig for validating correct calibration circuit function.

The implementation of ***best practices in systems engineering*** entails the use of an engineering portfolio approach to manage the entire suite of technical and engineering activities that underpin programmatic activities. Projects are identified and cataloged, with standard templates used to describe and report project activities. Engineering portfolio reviews provide an opportunity for managers and engineering staff from across Instrumentation Services—IRIS staff and subawardee staff—to share and report progress and technical details of their projects. This

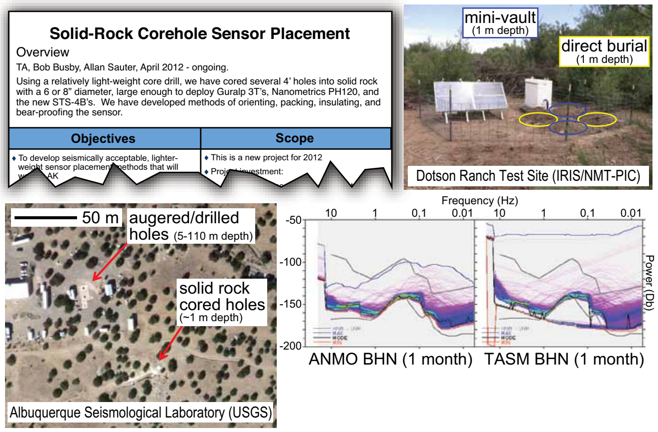


Figure IS-2. Instrumentation Services is coordinating a variety of sensor emplacement tests - summarized in this notional graphic. Test plans and project status are briefed to the entire IS Team as part of the IS Engineering Process (upper left). Testbeds are created, ranging from soft soil installations representative of typical portable installations (upper right), to shallow solid rock and intermediate depth boreholes co-located with a USGS-operated GSN site (lower left). Data are analyzed using Power Spectral Density techniques and other tools (lower right - from IRIS DMC automated QC processes) to measure results. The goal is to identify cost efficient emplacement strategies that yield optimum performance for different field conditions, using documented techniques that can be scaled to experiment goals and budgets.

process facilitates a comprehensive sharing of information and often establishes connections and cross-project synergies that were not previously exploited.

Finally, ***best practices in management*** means taking a team approach to Instrumentation Services. IS managers meet regularly as a team to review program status, identify issues, and coordinate activities. Subaward and procurement plans are reviewed and compared to identify potential synergies or savings. Routine policies and procedures that impact day-to-day efficiency are reviewed and refined. Plans and interactions with other programs or directorates within IRIS are identified and often consolidated. Communication with IRIS governance structures is also enhanced. For example, the committees that advise IS programs have held joint and/or overlapping meetings and IS managers coordinate materials so that committees are presented with a common level of detail. The Board receives integrated briefings and can now take a more pan-IRIS approach to instrumentation—by providing guidance and feedback on behalf of the community that is implemented consistently and appropriately across all IS programs.

Looking ahead, several new activities provide significant benefits across all of IS and will be managed and coordinated as pan-IS activities rather than executed within any one IS program. These activities, described in Section 3.1.8 (IS Coordinated Activities), include two key technology demonstration efforts, a seed effort to grow a future international program, and structured promulgation of instrumentation best practices. These activities form a suite of investments in the future of IRIS instrumentation facilities and services. The New Technology effort is particularly important as it will leverage emerging technology to create instrument systems that are smaller, lighter, use less power, and cost less. This effort is of interest Consortium-wide, and IS has motivated and facilitated discussions that have already engaged a large part of the community (as discussed further below).

The entire set of Instrumentation Services activities are discussed in the following subsections, including the new IS Coordinated Activities.

Proposed Activities

3.1.1. MANAGEMENT

All of IRIS' instrumentation-related senior management are pulled together in an IS management team to ensure tight coordination. Under the leadership of the IS Director, this team oversees all of IRIS' instrumentation programs, with each of the senior staff leading one or more major efforts. Each manager oversees staff, budgets, subawards, and procurement. As a team, this group engages in coordinated planning and budget preparation—among themselves, pan-IRIS and with the Coordination Committee and the Board. In cases where subawards serve multiple projects the work statements are coordinated and consolidated (e.g., the New Mexico Tech subaward activities are coordinated across Portable Seismology, TA, and Polar Support Services). Procurements with equipment suppliers, both large and small, are coordinated and, where appropriate, bundled for better pricing and/or efficiency (e.g., sensors, station vaults, cellular modems). The Director of IS represents this IS management team on the IRIS Senior Management Team. This facilitates information flow and coordination, vertically and laterally, and ensures efficient use of the group's time.

3.1.2 GOVERNANCE

The community is involved in IS activities at a deep and fundamental level. The current governance structure includes standing committees for GSN and PASSCAL, a USArray Advisory Committee, a Polar Network Sciences Committee, and the Instrumentation Committee. Working groups have been created to provide more detailed technical guidance to the TA (the Transportable Array Working Group) and to MT (the Electromagnetic Working Group). The individual programmatic governance structures are described in greater detail below. As discussed earlier in the proposal, the IRIS Board of Directors is currently looking at the evolution of the governance structure and considering a more closely aligned overlay between governance and management. Given the tight communication and feedback already in place, IS can readily accommodate the evolution of the governance structure as needed/desired.

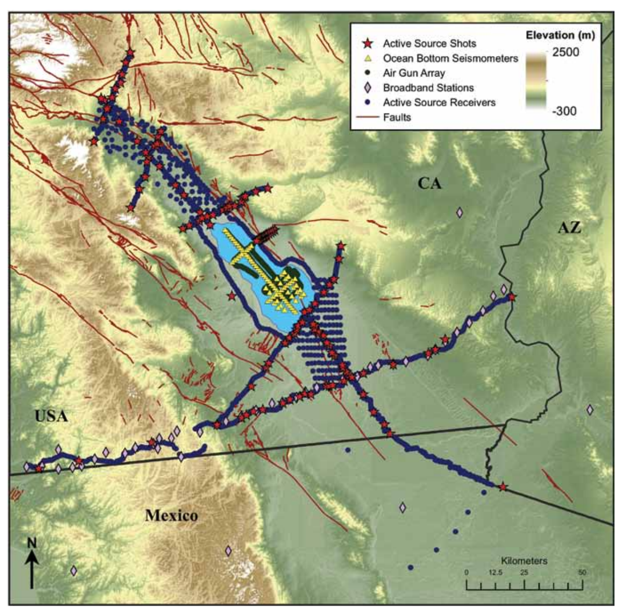
3.1.3. PORTABLE SEISMOLOGY

Portable Seismology provides instrumentation and expertise to support Principal Investigator (PI)-driven seismic data acquisition projects. The facility mobilizes equipment and personnel to support field experiments ranging from high-resolution subsurface imaging of fault scarps and groundwater resources to continent-scale investigations of tectonics and upper mantle dynamics, leading to a host of new discoveries about Earth. In addition to gathering data for fundamental research, Portable Seismology provides experience and training for the next generation of seismologists. Graduate students participate in the planning and implementation of almost all field deployments and the equipment is used for teaching by regular and Educational Affiliate institutions. The facility provides professionally supported state-of-the-art equipment, tools for standardized data retrieval and archiving, and advice and support in experiment logistics and planning. A turnkey facility approach allows the PI to focus on optimizing science productivity rather than supporting basic technology, engineering, and logistical expertise. Because few research institutions could create and maintain on their own the resources to stage modern large-scale data acquisition efforts, this IRIS facility vastly expands and democratizes the research community. By integrating instrumentation support, PI support, and data support under the direction of dedicated professional staff, IRIS has enabled the seismology community to mount hundreds of large-scale experiments throughout the world. An important aspect of the facility is standardization and archiving that make the acquired world-class seismic data sets freely available to all researchers and educators via IRIS Data Services.

Portable Seismology is a merger of the PASSCAL facility and the EarthScope USArray Flexible Array (FA). Since its inception in 1984, PASSCAL has supported over 900 experiments, including mobile arrays for recording of planned explosions, temporary deployments for aftershock studies, and longer-term deployments for observations of regional and teleseismic events. Starting in 2003, the PASSCAL model was incorporated within EarthScope as the Flexible Array, providing a separate set of instruments for experiments within the EarthScope footprint in North America. During this upcoming Cooperative Agreement, the FA and PASSCAL equipment pools will be merged into a single "portable" instrument pool. Responding to strong encouragement from the user community, the USArray Advisory Committee, and the PASSCAL Standing Committee to optimize facility resources and efficiency, the combined PASSCAL/FA pool will operate under a single set of policies governing instrument use, level of services provided to the PI, and the proprietary period granted to the PI for data analysis. The FA inventory will remain primarily dedicated to field projects funded by NSF's EarthScope program, but the full integration into a single Portable Seismology facility and attendant management flexibility will enable improvements and efficiencies in operations.

High-Resolution Seismic Studies of the Lithosphere

New science objectives are achievable with larger-scale deployments that are made possible by joint use of the instrument pools and combined staff expertise represented by the USArray Flexible Array, PASSCAL, and ocean bottom seismometer programs. For example, the Salton Seismic Imaging Project (Han et al., 2011) will create a unified geometric model of the San Andreas, Imperial, and other faults that control the rifting and contribute to earthquake hazard in Southern California today. Instead of leading to seafloor spreading as in the Gulf of California, rifting here was affected by rapid sedimentation from the Colorado River and magmatism from below, which together added new continental crust more than 20 km thick. The dense, wide-aperture experiment is needed to image the structure of sedimentary basins in the Salton Trough and the three-dimensional distribution of seismic wavespeed in the crust and uppermost mantle.



The goals of the Salton Seismic Imaging Project are to understand the initiation and evolution of nearly complete continental rifting in the Salton Trough and improve earthquake hazard models. In this map, red lines are faults while symbols are seismic sources or seismographs (see legend).

PASSCAL has influenced academic seismology in all parts of the world explored by US seismologists by providing instrumentation to spur or augment international collaborations and by introducing and supporting standardized digital data collection and field techniques to scientists in developing nations. Many of the standards and facilities pioneered by IRIS for instrumentation and data collection, archival, and open exchange have been adopted by other seismological networks and portable facilities in the United States and worldwide.

Through the years, PASSCAL has led exciting technical development efforts critical to the advancement and success of observational seismology. Initially, the program pioneered the development and use of portable systems based on 24-bit data acquisition systems and low-power, portable, three-component, broadband force-feedback sensors, with GPS absolute-time-base clocks and compact, high-capacity hard disks. In the early 1990s, PASSCAL collaborated with the University of Texas system to produce a highly portable and very easily deployed, single-channel recording system (the "Texan") for use in controlled-source experiments and rapid deployments for earthquake aftershock studies. The advent of the EarthScope Flexible Array program in 2003 nearly doubled the size of portable instrument pool (both broadband and higher frequency). In this proposal, activities are proposed (WBS 3.1.8) to initiate the development of a new generation of portable systems that will alleviate pressures on the current pool and open up significant opportunities for new science.

During the past year, the combined portable programs (PASSCAL and FA) supported over 70 new experiments, and helped to archive more than 6.4 Tb of data in the IRIS Data Management Center for public access. Portable Seismology resources remain fully subscribed for use in peer-reviewed research programs, which confirms the importance of this facility to the Earth science community. Indeed, despite long-term growth in the size of the instrument pool, demand for instruments and technical support continues to rise. Demand and capacity remain major concerns, and balancing instrument inventory with scheduling requirements is an ongoing challenge.

Program Operations

Instrument and Institutional and Resources. Table PS-1 provides an inventory of the combined PASSCAL and FA instruments to be supported by Portable Seismology. These scientific-grade systems are maintained, organized, and prepared for shipment worldwide in configurations from a few to a several thousand at a time, based on requirements specified by the research PIs. In-field data collection can last from days to years. PASSCAL Instrument Center (PIC) staff provide extensive pre-experiment training and assistance to PIs and can be available for limited advice and support in the field, but PI grants are responsible for the costs of field logistics and other experiment-specific activities, including shipping, installation, operation, and demobilization. The IRIS instrument pool is in near-constant use, often in harsh field conditions, and is thus subject to significant degradation over time. Sustaining this resource through testing, repair, and replacement of failed components is a major effort at the PIC.

Equipment requests for funded experiments presently conscript much of the existing inventory for the next few years. During the upcoming Cooperative Agreement, the facility will sustain the inventory of "traditional" broadband and high-frequency instrumentation at the current level, which is sufficient to support approximately 70 experiments per year as presently funded to the PI community. The Portable Seismology budget does not request funds for significant investments in acquiring new permanent equipment under this proposal, in light of proposed developmental work focused on future instrumentation. We will take two approaches to maintaining the current equipment inventory. First, we will continue our rigorous maintenance and repair program using in-house repair capability. Second, some broadband systems from the TA will become available as it migrates to Alaska, and these systems will be selectively used to replace failed or damaged equipment in the Portable Seismology pool.

The majority of Portable Seismology support activities are implemented through a major subaward to New Mexico Tech (NMT), which staffs and operates the IRIS PIC in Socorro, NM, and through a minor subaward

Table PS-1. Sensors and dataloggers included in the inventory of portable instruments at the PASSCAL Instrumentation Center in Socorro, NM. This includes the current PASSCAL and USArray Flexible Array (FA) instruments, a set of 10 instruments held on reserve for aftershock response (Rapid Array Mobilization Plan [RAMP]) and specialized cold-temperature Polar instruments acquired under the NSF OPP-funded Polar Support Services (WBS 3.1.5). This inventory does not include the ~420 broadband systems used in the USArray Transportable Array (WBS 3.1.6) described in a later section.

	PASSCAL	Polar	USArray FA	RAMP	Total
Datalogger 3-Channel	834	48	419		1301
Datalogger 6-Channel	26	3	50	10	89
Datalogger 1-Channel (Texans)	902		1698		2600
Broadband Sensor	505	75	354		934
Intermediate-Period Sensor	104	6		10	120
Short-Period Sensor	177		137		314
High-Frequency Geophone (3 CH)	560		303		863
High-Frequency Geophone (1 CH)	1230		1710		2940
Accelerometer	9		20	10	39
Multichannel (60 channel)	21				21

to University of Texas, El Paso (UTEP), to support a UTEP-owned pool of active-source recorders (Texans) and to provide active source expertise. The Socorro PIC is housed in a 35,000 sq. ft. building, provided by NMT, with extensive office, laboratory, and warehouse space, including a number of seismometer testing vaults and local field sites (Figure PS-1). In addition to the staff that supports the Portable Seismology effort, staff at the PIC include personnel that support Polar Support Services and TA efforts. The subawards to NMT and UTEP are predominantly for salary and associated infrastructure costs for professional staff to carry out the program tasks listed below. IRIS directly purchases all major equipment items and most supplies and expendable materials used during experiments. In addition, costs for insurance, shipping, maintenance contracts and travel for management, subaward staff and committees are also budgeted as direct IRIS expenses.

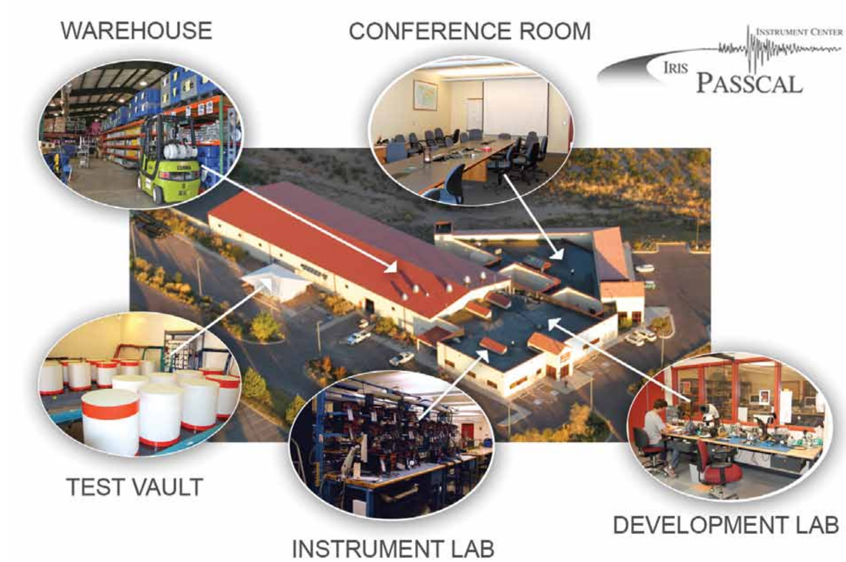


Figure PS-1. PASSCAL Instrument Center at New Mexico Tech in Socorro, NM.

Program Services. In providing "turnkey instrumentation system support," Portable Seismology must respond to the user community in the acquisition and maintenance of standard and specialized hardware and in the important and highly visible area of project support, which includes planning, training, field assistance, and data support provided by PIC staff to PIs, and to their students and staff. The key Portable Seismology service areas are:

- ***Management and Governance:*** Provide technical advice, leadership, strategic planning, and oversight of operations for Portable Seismology in partnership with and on behalf of the scientific community, and continue community engagement through support of advisory committees and reporting to the IRIS Board of Directors.
- ***Instrumentation Support:*** Continue to provide and maintain an extensive pool of high-frequency, short-period, and broadband recording systems and associated support equipment.
- ***PI Support:*** Provide user services to train and support NSF-funded PIs, their staff, and students in carrying out portable field experiments, including training in instrument and software use and the facilitation of active sources.
- ***Data Support:*** Provide user services to PIs to assist in data collection and in the preparation of data for archiving and redistribution at the IRIS Data Management Center.
- ***Engineering and Technology Development:*** Provide engineering support for instrumentation and technical applications to sustain existing equipment and to assist in the integration of new technologies into both Portable Seismology and throughout IRIS Instrumentation Services.

Integration Across IRIS. In addition to internal improvements in management from the merging of resources within Portable Seismology, links within the new Instrumentation Services structure will strengthen the sharing of technical and operational knowledge with Polar Support Services, the Global Seismographic Network, and USArray Transportable Array, and with data management activities under Data Services. Portable Seismology also provides key support to the broader IRIS mission through linkages with Education and Public Outreach, and International Development Seismology.

Scientific justification

PASSCAL and the FA have provided resources to assist research seismologists in a total of more than 900 experiments spanning all 50 states, all seven continents, and 58 countries. Experiments have come in all shapes and sizes, ranging from small deployments (N=1–5) in hard-to-access or other special locations (e.g., to study seismicity associated with icebergs or calving glaciers; Martin et al., 2010; O'Neel et al., 2010; Walter et al., 2012); to modest-sized rapid-response deployments (N=10) to capture aftershocks (e.g., most recently in Oklahoma and Virginia; e.g., Keranen et al., 2012); to moderate-sized deployments (N=100) for characterizing tectonic tremor in subduction zones (e.g., Cascadia; Ghosh et al., 2010); to large active-source crustal imaging experiments (e.g., more than 2900 sensors used recently in the Salton Sea Seismic Imaging Project; e.g., Han et al., 2011; Fuis et al., 2012; and more than 1500 sensors used during the 2009–2012 Bighorn Project; Miller et al., 2010; Yang et al., 2012).

Hundreds of US-based PIs and their students have been directly involved in portable deployments through the PASSCAL program and, more recently, through the FA component of the EarthScope USArray program. In addition, scientists from around the globe presently download approximately 40 Tb of data per year from portable data sets archived at the IRIS Data Management Center (DMC). These data are used both for established avenues of inquiry and for follow-on scientific studies that were frequently not envisioned by the original PIs. The program has enabled scientists to efficiently deploy instruments in numbers and locations, and to collect data volumes, that would otherwise not have been possible. In so doing, IRIS has enabled scientific studies that have produced fundamental advances in knowledge of lithospheric and asthenospheric structure at multiple scales, in the nature of seismic sources (both previously known and novel), in the evolution of fault zones over time, and in increasingly detailed images of near-surface structures and processes relevant to society. Some of the scientific highlights from portable experiments are described in the earlier Scientific Justification section of this proposal and in the *Seismological Grand Challenges* report (Lay, 2009).

One of the more important classes of investigations where IRIS Portable Seismology has played an essential role is in large-scale, multi-institutional and multidisciplinary studies in areas such as the Himalayas (e.g., Karplus et al., 2011), the northwestern United States, and Yellowstone system (e.g., Obrebski et al., 2010), the North America Cordillera (e.g., Levander et al., 2011), the San Andreas and Sierra block systems (e.g., Schulte-Pelkum et al., 2012), and South America (e.g., Bezada et al., 2011; Russo et al., 2010). Methodologies and technologies pioneered with IRIS portable instrumentation support have furthermore been leveraged in recent years to facilitate trailblazing experiments in Antarctica, Greenland, and other polar regions (see WBS 3.1.5 Polar Support Services). The seismological components of these experiments, many of which have involved significant international collaborations, have made fundamental contributions to our understanding of lithospheric dynamics, mantle structure, and continental evolution within the global tectonic system.

Proposed Activities

The scientific interests of the seismology community continue to evolve, and Portable Seismology seeks a balance between supporting ongoing seismology science objectives, while at the same time facilitating the use of portable instrumentation to address new and emerging scientific goals. Additionally, a number of other science communities have "discovered" the PASSCAL program and are increasingly using seismology in novel ways to complement and extend their disciplinary scientific interests. For example, Polar Support Services is the product of adapting and extending program resources to enable new science objectives in challenging and harsh environments and in support of new scientific interests in cryospheric dynamics. During the next five years, we plan to continue cultivating these relationships in areas such as the glaciology, ocean bottom seismology, atmospheric science, ocean science, and volcanology.

A dedicated and well-trained staff that can focus on the unique requirements of supporting portable experiments is a critical element in sustaining the investments that NSF has made through the years in portable seismology resources. Key areas of attention include: sustaining PI support to deploy instruments and to collect and utilize high-quality data; modernization and enhancement of strategic data support for quality control and for archival and redistribution; participation in Instrumentation Services-led instrument development; ongoing system upgrades and maintenance of existing field equipment; documentation of best practices

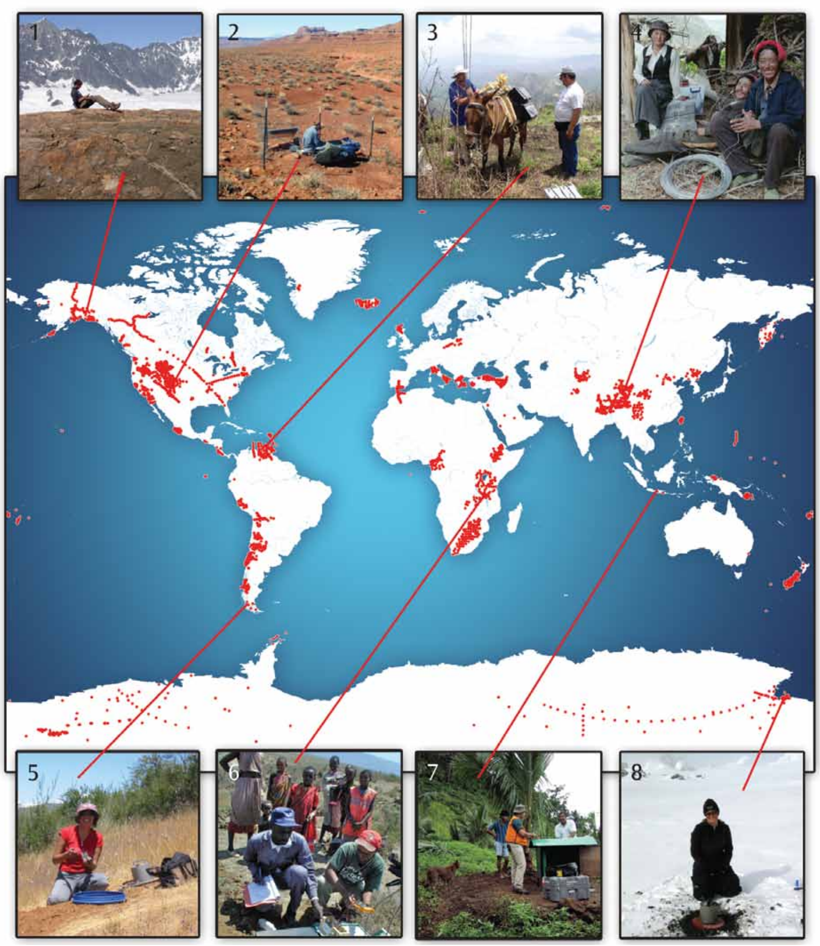


Figure PS-2. Global extent of station coverage for the history of the PASSCAL program, now totaling more than 3800 stations. Photos: (1) Alaska. STEEP experiment. (2) La RISTRA,New Mexico. (3) Venezuela. Transporting gear the old fashioned way. (4) Tibet. Locals help with installation of a station. (5) Chile. Installing an intermediate period sensor. (6) Kenya. A short period station being serviced while local Masai look on. (7) Tiwi. Specialized enclosure for a rainy environment. (8) Mt. Erebus. An intermediate period sensor is installed directly onto the bedrock flanking the volcano.

for both field work and data management; and expanded support for active sources.

3.1.3.1. MANAGEMENT

The primary management activities are to guide operations and the PIC through the NMT subaward, to coordinate operations with other components of IRIS Instrumentation Services, to interact with IRIS and other community governance, and to interface with NSF and the PI community on instrumentation needs and scheduling. The Program Manager (PM) provides technical advice and leadership in the operations and development of the program, and serves as the primary interface between the program and user community. The PM attends meetings of advisory committees and represents the program at IRIS Board of Directors meetings. The PM, along with Instrumentation Services management, also coordinates new program developments with a particular focus on improved instrumentation and leveraging best practices and knowledge among Portable, Polar, GSN, and USArray operations.

3.1.3.2. GOVERNANCE

In the past, advice to guide the activities of Portable Seismology has come from the PASSCAL Standing Committee, the USArray Advisory Committee, and the joint IRIS/UNAVCO Polar Networks Science Committee. With the merging of the PASSCAL and USArray FA and the extended management integration under Instrumentation Services, we are exploring ways to streamline the governance structure while maintaining an effective, efficient, and transparent forum for community input directly to the IRIS Board and senior management. This is a particular challenge as the PASSCAL user community grows in both depth and breadth of its supported science. IRIS management will continue to work with the community to sustain the best possible governance structure to oversee and guide Portable Seismology in providing the research community with high quality instrumentation and services, and to continue to adapt to meet evolving scientific needs.

3.1.3.3. OPERATIONS

Instrumentation Support. The instrument pool requires personnel and facility resources at the PIC to maintain the equipment, to perform integration of new equipment into the pool, to test complete systems, and to manage inventory, storage, packing, and shipping. Maintenance of the pool requires ongoing repairs and replacement of items to ensure that the numbers of high-quality and well-calibrated instruments available to the scientific community remain sufficient to support funded experiments. As noted above, this proposal does not request funds for any substantial growth of the pool. During the upcoming Cooperative Agreement, we will work to sustain an already aging instrument pool and

Figure PS-3. A field scientist prepares to deploy a broadband system as part of the active-source seismic experiment near the Bighorn Mountains, WY, 2010.

provide input and guidance into new engineering and technology developments, in collaboration with other parts of Instrumentation Services.

Principal Investigator Support. PI Support includes assistance to funded investigators through planning, logistics (including packing, shipping, and, for international projects, support in the exporting and importing of equipment to/from the United States), deployment training, software support, data handling, and in-field support (as requested and necessary). As field investigations have expanded in recent years into new areas with harsher physical environments, demand for experiment support and specialized components have grown steadily. A key premise of PI Support is that PIC-based experiment support is pivotal to optimizing PI success and to improving data quality and return rates. In the next five-year period, it is critical that we maintain and continue to improve the high level of support provided to PIs by the PIC. In collaboration with other Instrumentation Service programs, increased effort will be dedicated to documentation of best practices and distribution of these materials through the Web and via in-person interactions and training courses and materials. As next-generation instrumentation emerges out of the IS technology development effort, Portable Seismology will be responsible for supporting the initial use of these instruments in demonstration deployments.

In recent years, the active-source crustal imaging community has called for programmatic-level support for special services related to permitting and access to active seismic sources (explosions and vibrators) that are used in reflection and refraction studies of the crust. We will support an expanded role for land-based active sources by including a subaward to UTEP to make their long-standing expertise in controlled seismic sources available to academic seismic projects, and to provide training for permitting and deploying explosive shots.

Data Support. As a requirement for the use of NSF-supported equipment and experiments, PIs are responsible for

Figure PS-4. PASSCAL field engineers programming Texan recorders for the Salton Seismic Imaging Project, 2011.

delivering data to the IRIS DMC for standardized archiving and for effective and efficient global redistribution. The Data Support group based at the PIC assists PIs with data quality issues related to conducting portable seismic experiments, and with preparing data and metadata for submission to the IRIS DMC for archiving and public access as soon as possible after they are collected from the field. A critical part of this process includes reviewing data continuity and verifying metadata and waveform quality in data sets recorded in the field, thereby ensuring data consistency and quality in the DMC archive. To minimize the impacts on PIs associated with larger experiments that generate very high volumes of data, and to make current data collection more efficient, we will continue to develop higher levels of data service. For the next five years, this will involve improvements in software to provide efficient "dirt to desktop" PI support, standardized across the entire Portable Seismology effort, for approximately 70 experiments per year.

Engineering and Technology Development. As PIs ambitions continue to challenge the limits of instrumentation technologies, Portable Seismology is actively seeking technical and engineering solutions to keep pace with changing and growing scientific demand. The current two-year wait time for broadband instruments for funded NSF grants clearly indicates that it is critical to maintain the current capability in portable broadband seismology. To maintain a viable pool of instruments and provide better techniques for data collection, we will continue to pursue incremental development and modifications to existing systems, in collaboration with instrument manufacturers. This effort will include specific focus on improving broadband sensor performance, power systems, and communications. For example, a key area of development for the existing instrument pool includes power system upgrades through improving battery technology and better engineering and system integration. Installation techniques for broadband seismometers are critical for ensuring high-quality recordings with minimal noise and site effects, and new techniques are needed particularly as PIs push deployments into in new, remote, and increasingly harsh environments where standard vault-style deployments are logistically difficult, and/or wish to efficiently deploy greater numbers of instruments in individual experiments. The engineering and technology issues, and developments resulting from these efforts, will have relevance across multiple IRIS programs and will be coordinated through Instrumentation Services.

As the USArray TA transitions to Alaska, we anticipate that there will be increased interest in deploying complementary portable experiments in the Alaskan and in other harsh environments. This will require instrumentation that is specifically designed for cold, wet, icy, and dark environments and exposed to hostile fauna (bears). For such environments, robust equipment that is lightweight and easy to deploy is critical. These issues are shared with Polar Support Services. Technical solutions can take many forms and will depend on the specific type of deployments planned. The unique needs of harsh environmental conditions will be met by modifying a component of the current Flexible Array and PASSCAL equipment pool.

An important development under Instrumentation Services will be to respond to the long-standing community interest in deploying larger numbers of sensors in arrays or networks (see WBS 3.1.8 IS-Coordinated Activities). By the end of this Cooperative Agreement, we anticipate that our proposed development efforts will have led to a new generation of data recorders, sensors, and equipment packaging that will be smaller, lower power, easier to deploy, and more capable of operating in extreme environments for extended periods. Coordinated at the Instrumentation Services level, the Portable Seismology staff will test and prototype these systems, and will conduct field operations and data support for pilot experiments. Thus, over the next five years, Portable Seismology operations will remain focused on providing the research community with a stable pool of existing research-grade seismic instrumentation, while working with Instrumentation Services toward the development of new portable instrumentation technologies to advance the horizon of seismology and associated science.

3.1.4. GLOBAL SEISMOGRAPHIC NETWORK

The Global Seismographic Network's 153 stations are now sited on all seven continents, from the South Pole to the high Arctic. This broad Earth coverage has been made possible with the cooperation of over 100 host organizations and seismic networks in 70 countries worldwide (Figure GSN-1). GSN data are freely and openly available to anyone via the IRIS DMC.

The GSN is operated and maintained through a partnership between the USGS and IRIS. Funding for GSN operations is proportionate to the number of stations operated by each group: core IRIS funding from NSF covers approximately one-third of the total operation cost. (The University of California, San Diego, International Deployment of Accelerometers [UCSD-IDA], operates and maintains about one-third of the core network through a subaward from IRIS, and the USGS' ASL operates the other two-thirds). In addition to providing essential data for basic research, GSN data play a key role in mission-critical earthquake hazards-related applications by US and international agencies. The GSN is a vital source of data used by government agencies such as the USGS to rapidly estimate earthquake locations, assess long- and short-term earthquake hazards, and provide intelligence needed to guide rapid earthquake emergency response. The GSN also provides critical data to scientists and operations at NOAA Tsunami Warning Centers, providing many of the critical real-time observations needed to define their rapid analysis of globally distributed earthquakes with tsunamigenic potential (Newman et al., 2011). The GSN is a member of the Global Earth Observing System of Systems and the network operation contributes substantially to the International Monitoring System for the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO). Thirty-one GSN stations and seven GSN Affiliates are linked directly to the CTBTO International Data Centre. GSN network management is closely coordinated with other international networks through the FDSN.

GSN stations are designed to record seismic signals ranging from high-frequency strong motions to ultra-long-period free oscillations and tidal motions. Recording this broad seismic energy spectrum requires specialized sensors, high-fidelity recording systems, and an infrastructure that minimizes natural and cultural noise and provides thermally stable and physically secure operating environments.

Over the past several years, the GSN has benefited from NSF and USGS augmentation funds—provided through the American Recovery and Reinvestment Act (ARRA)—to procure and install the next generation of data acquisition systems and to update some of the aging GSN site infrastructure. The new systems provide higher dynamic range, reduce power consumption, and reduce logistics costs. In addition, funds for secondary sensor systems have permitted the addition of redundancy to the broadband sensor recordings and expanded the community's ability to compare broadband sensor quality (funds via DOE and ARRA). These upgrades will be substantially completed by October 2013, and we are in the process of updating the Quality Assurance System (QAS) to ensure that both current stream and archived GSN data are of the highest possible quality.

Scientific Justification

For the last three decades, the GSN has facilitated substantial progress in imaging Earth's interior and earthquake processes. The box on the next page illustrates one representation of this progress, and shows the model s40rts in two different spherical-harmonic (wavenumber) bands: one comparable to what was possible in the early 1980s, and the other illustrating enhanced resolution available following a few decades of observations with the GSN and openly shared international facilities. These comparisons represent a minimal view of our advances. To transform these images into a more complete, accurate, and higher-resolution view of Earth's interior, we must continue to invest in the GSN and to develop systems that ensure the highest-quality observations are obtained. Although the GSN has already set a very high bar for the quality and completeness of global seismic network operations, even more vigilance in high-quality operations and data quality assurance will be required to allow researchers

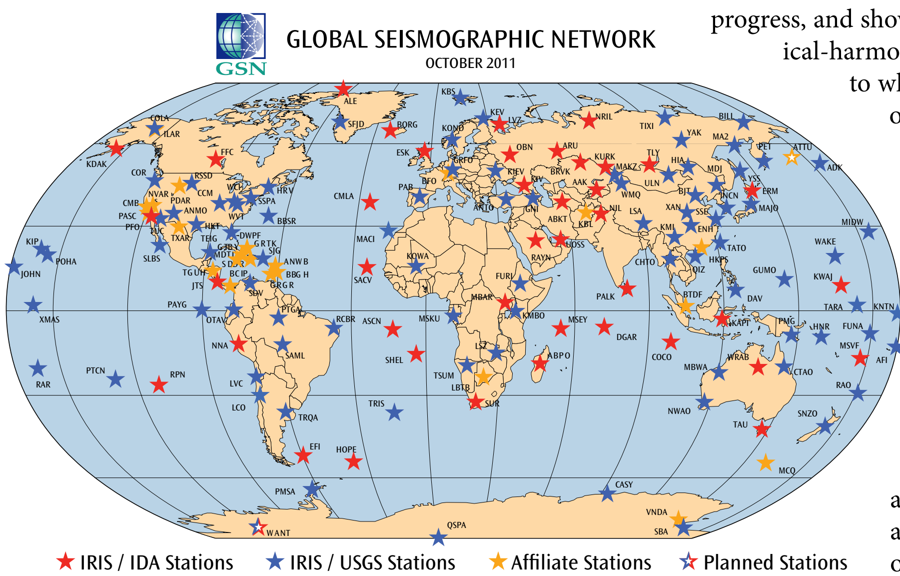


Figure GSN-1. The current Global Seismographic Network configuration includes 80 IRIS/USGS, 41 IRIS/IDA, 10 IRIS/China–USGS, and 22 GSN Affiliates (including USGS Caribbean Network of nine stations).

to exploit enhanced analytical techniques, such as those involving amplitudes and waveform anomalies, to advance the resolution of Earth's anelastic and anisotropic characteristics.

The availability of a uniform and high-quality set of seismic observations has enabled construction of increasingly refined catalogs of earthquake location, size, and faulting geometry. The National Earthquake Information Center and the International Seismological Centre earthquake catalogs are globally complete down to a magnitude in the range 5.0–5.5, and the global centroid moment tensor catalog provides close to 35,000 estimates of earthquake size and faulting geometry, which is a valuable resource for seismic and tectonic investigations (Ekström et al., 2012). Recently, GSN, PASSCAL, and USArray data (in conjunction with UNAVCO and PBO data) have been used to study plate-boundary slip processes and slow-slip events in Cascadia and other subduction zones. The GSN has been a critical resource in efforts to map the kinematic processes of the increased number of very large (M~9) megathrust earthquakes in recent years (e.g., Sumatra, Chile, and Japan) (Ide et al., 2011). High-fidelity recordings of these "megaquakes" have illuminated source processes that suggest such events may differ in important ways from typical major and great earthquakes as noted in the Introduction. Although there have been tremendous advances in estimating Earth's elastic structure, the imaging of Earth's anelastic and anisotropic properties is still in its infancy. Joint interpretation of models of elastic, anelastic and anisotropic structure offer an opportunity to separate the effects of composition and thermal structure. This step is critical for understanding deep mantle structure, Earth's dynamic history, and current global geologic processes. Seismic imaging of Earth's interior requires waveform data of the highest quality. It is particularly important to have precise knowledge of the instrument response to ensure accurate measurements of seismic-wave amplitude and phase. These observations are sensitive not only to anelastic structure but also to short-wavelength elastic structure through focusing effects; they are therefore a potentially rich but currently underutilized data set for probing the mantle (Lay and Garnero, 2011). High-precision, absolute calibrations are required to distinguish between instrument effects and Earth properties.

In addition to its basic science motivations, it is important to recognize that the GSN plays a key role in many monitoring efforts around the globe. Any modification of the GSN must consider the impact of station deployments on those monitoring organizations whose missions rely on the network and for which it gains strong interagency support. The groups include the hazard-related missions of the earthquake and tsunami monitoring communities mentioned above, as well as CTBTO treaty stations.

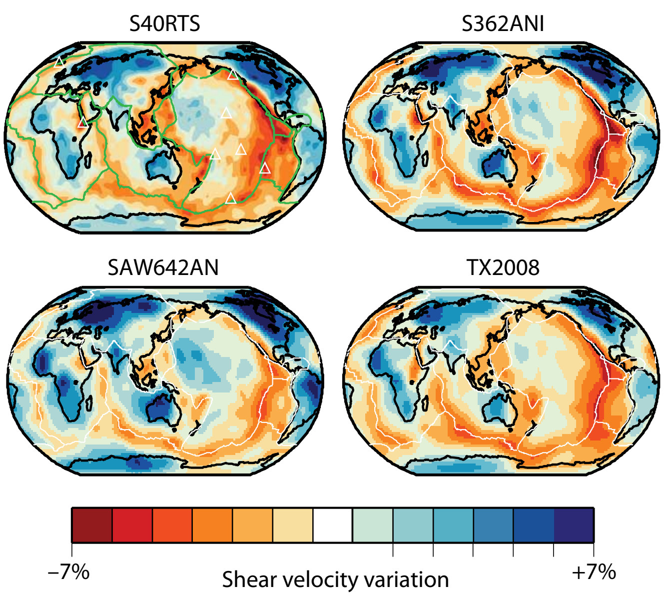


Figure GSN-2. Maps of the variation in shear-wave velocity at a depth of 100 km for models (upper left) S40RTS (Ritsema et al., 2011), (upper right) S362ANI (Kustowski et al., 2008), (lower left) SAW642AN (Panning and Romanowicz, 2006), and (lower right) TX2008 (Simmons et al. 2009). These models were obtained via a variety of modeling and regularization algorithms, yet yield highly consistent results, in both pattern and amplitude—illustrating the significant impact of the GSN's global data coverage. The models have 10 to 20 times the resolving power of models developed during the infancy of the GSN and exhibit consistency even in smaller details, such as the variation in structure beneath West Africa or northern Eurasia. Other models are embedding dense regional datasets, such as the Transportable Array, within the global data sets to create self-consistent global-regional models.

Proposed Activities

3.1.4.1. MANAGEMENT

The GSN is managed by the GSN Program Manager (PM) who is a member of the IRIS Instrumentation Service management team. The PM coordinates GSN activities with the USGS-GSN program, and provides technical advice and leadership in the development and evolution of the GSN program and represents the program (along with the GSN Standing Committee chair) to the IRIS Board of Directors. The PM is the technical representative on all GSN subawards and contracts, including the UCSD-IDA operations award, and manages the budgets, program plans, and administrative coordination on GSN matters. The PM draws administrative and technical assistance from IS staff members as needed and coordinates administrative matters with the IRIS Financial Services and Sponsored Projects offices. GSN management also includes interactions with those government agencies who use GSN data (USGS, NOAA, and the Departments of Defense, Energy, and State), as well as all foreign partners in GSN and FDSN operations. The PM is the FDSN backbone representative for IRIS.

Management of the network operators under the IRIS GSN program is provided by the ASL Scientist-in-Charge for the USGS portion of the network, and by the Project IDA PI and Executive Director for the UCSD subaward portion of the network.

3.1.4.2. GOVERNANCE

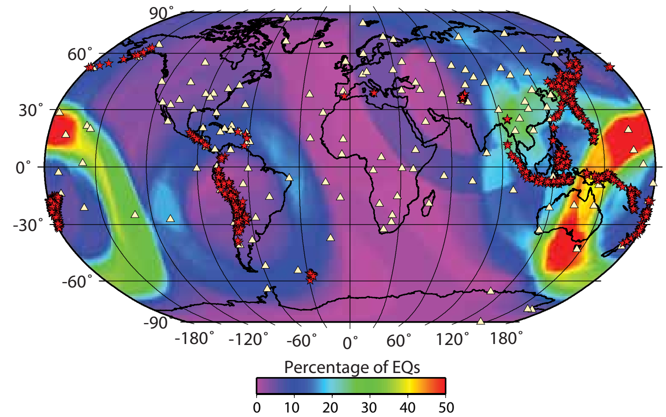
Community input to the GSN is achieved via the GSN Standing Committee (GSNSC). Its members are selected from IRIS member institutions and international operators with partnerships with the GSN. In addition, the GSNSC serves as the steering committee for the USGS GSN program and so includes a permanent member of the USGS GSN program in a voting role. The GSNSC meets twice per year and the chair represents the committee at Board and other IRIS committee meetings.

3.1.4.3. OPERATIONS

One of the GSN's strengths comes from the decades-long consistency of the network. Therefore, the primary and most important activity of the GSN program is the continued operation and maintenance (O&M) of the network. IRIS/NSF funds basic O&M for 41 GSN stations through a subaward to the UCSD-IDA program, and the USGS directly funds 90 stations (IRIS/USGS) through its ASL, with substantial coordination and collaboration between the groups. The remaining 22 stations in the network (known as GSN Affiliate stations) receive funding from outside the IRIS/NSF GSN program, although the USGS funds nine of these stations (the Caribbean network).

Both network operators fulfill similar functions in operating and maintaining the GSN. Field, facility, and software personnel must manage the stations—not only the equipment (sensors, data acquisition, power, and telemetry), but also the data flow and metadata to ensure well-calibrated systems. Equipment must be procured, received, tested, integrated, inventoried, warehoused, shipped, and repaired. Station information, maintenance and installation reports, records of system modifications, export licenses, and shipping documents, supplies, and equipment schematics must be organized and maintained. Software must be maintained and tested across a variety of station configurations and throughout the data collection system, from the station data acquisition system, to the telemetry interface, to data archiving and delivery, to the IRIS Data Management System (DMS). Station state-of-health, telemetry systems, and data quality control must be monitored routinely. Close collaboration among GSN operators, Data Collection Center (DCC) personnel, and the IRIS DMC is essential to diagnose and resolve data-quality problems and ensure the data user community is aware of all issues that affect data quality. In addition to equipment and data issues, it is critical to establish and maintain a rapport with the local host institutions (often relationships that extend over decades) to optimize station operations.

The dedicated technical staff at the network operation centers is a key component in successful GSN operations. The staffing levels at IDA and ASL maintain about one-third and two-thirds of the GSN, respectively. Data availability from the network has been above the performance goal of 85%, and there are signs of significant improvements in this metric with the upgrade to the next-generation acquisition systems (Figure GSN-4). The acceleration of GSN upgrades, initiated in 2009, included supplemental personnel at IDA and ASL, as well as augmented travel support. By reducing the burden of maintaining obsolete equipment, the productivity and efficiency of our GSN field staff with the new standard equipment will permit increased emphasis on improved data quality for the whole network.



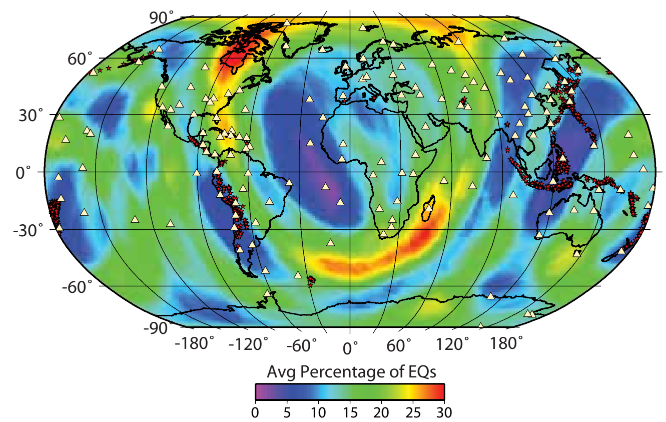


Figure GSN-3. Various seismic phases from deep earthquakes (red stars) have been modeled to determine optimal station coverage to maximize the data return from these events for target phases of interest. The top figure shows ScP phases (for detecting ultra low velocity zones) with higher hit counts in warmer colors and lower hits in the cool colors. The current GSN is shown in beige triangles. Similarly, the lower image shows other core-mantle boundary phase "sweet spots." Using models like this, we can determine optimal strategic GSN deployments for maximum scientific return.

As part of evolving and enhanced O&M, the GSN proposes to optimize station performance and data return, improve quality data, and assure robust operations of the network through the next five years and beyond. Significant activities associated with the challenges are:

- Optimizing station performance
  - Selectively refurbishing station infrastructure

- Selectively relocating and/or strategically densifying station coverage
- Enhancing the quality assurance effort
- Searching for the next-next generation systems and sensors

Optimal Station and Network Operations. To optimize network operations, new operational modes will be considered that include, but are not limited to: redistributing stations between network operators, relocating stations from highly covered areas to areas with sparse station spacing, relying on host countries to provide more operations support, and re-evaluating GSN specifications and station design to minimize long-term costs. Although redistributing GSN station operational responsibilities between the two network operators may not always reduce costs significantly, it may be possible to reduce the management burden through the re-evaluation of GSN station grouping and by introducing cost savings through optimization of O&M at the two depot facilities. There are aspects of operations and international collaboration/coordination that benefit from joint network operations by both a government entity and a university partner.

As the GSN ages, optimal operations may require occasional changes to civil works and infrastructure, including relocation of a few GSN stations. Changing to more secure and reliable sites has the potential to reduce the number of visit to stations and permit strategic relocation to improve station performance, minimize costs, or enhance the GSN resolution over specific targets of interest, as determined by the GSNSC in coordination with the monitoring communities.

Quality Assurance System. During 2011, IRIS, in collaboration with the USGS/GSN, the GSNSC, and the GSN network operators at the ASL and UCSD, began to implement a new

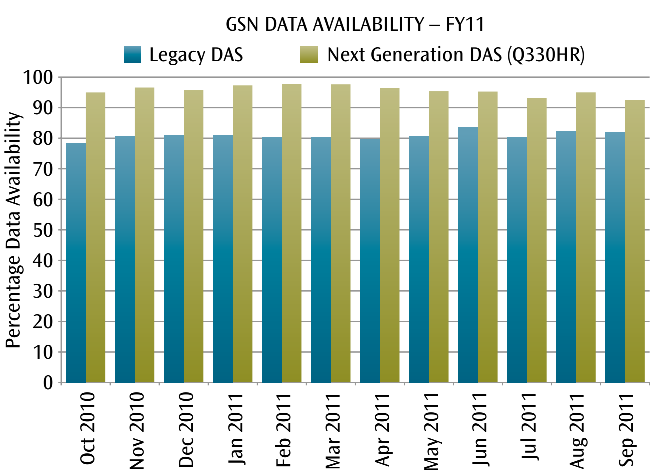


Figure GSN-4. The upgrade to the next-generation field system has resulted in marked improvement in the data return from the GSN. The chart shows the monthly average data return for FY11 from those station that had been upgraded (green bars) and those that still used the older GSN systems (blue bars). The annual average data availability for upgraded stations was ~96% versus 81% for non-upgraded stations.

data QAS. It defines new policies, procedures, metrics, and reporting schemes for describing GSN data quality, both within the operations community and to the data user community. Responsibility for implementation of QAS initially falls between the GSN operations centers and their respective DCCs. As a part of the overall DMS, the DCCs will coordinate and implement GSN data quality requirements in conjunction with the IRIS DMC. A new framework for implementing quality metrics within IRIS is underway and will be extensible to all IRIS data holdings. This effort will assure that the quality of data from the GSN is as high as possible and that the quality status of each station is clearly reported to the data user community. The QAS will provide a powerful tool for GSN management and governance to review station performance and prioritized investments in station operations and, as necessary, refurbishment, relocation, or closure. Through coordination between IRIS Instrumentation and Data Services, the GSN QAS will be expanded to all aspects of the IRIS facility that provide data to the seismological community, and existing quality programs will be coordinated.

Next-Generation Field Systems. The current "next-generation" field system (NGS) will continue to be supported by their manufacturers for at least the next five years. Thus, we can normalize our GSN operations to a set field system through this performance period. However, the current NGS vendor has indicated that as new technologies emerge and current components become obsolete, the GSN acquisition system may not be commercially available after 2018. Therefore, during the next five years the GSN community and operators will need to explore next-NGS (N-NGS). This process will entail the following steps:

- Identifying the technical specifications for the N-NGS
- Developing testing and acceptance criteria
- Testing and evaluating prototype technologies
- A formal procurement effort for the recapitalization of the GSN field systems

System development and testing can take several years, so it will be important over the next five years to reach a position from which this critical recapitalization effort may be initiated during the follow-on Cooperative Agreements (2018 and beyond). The proposed efforts within Instrumentation Services for the evaluation of new technologies will certainly be well coordinated across all IRIS instrument programs and GSN specification and design requirements will be included in that projects search and selection criteria.

GSN Primary Sensors. In recent years, the Streckeisen STS-1, the primary vault sensor for the GSN since inception in the mid-1980s, has shown signs of degradation in the stability of its long-period response at some stations. The failure rate of the primary borehole sensor (KS-54000) has also become unacceptable. Development of a replacement for these sensors was identified as major objective in the 2006 IRIS proposal and, with limited funding to IRIS and external support through the EAR Instrumentation and Facilities Program, significant progress has been made on new technologies and manufacturing procedures. Specifications for both vault and borehole sensor replacements have been developed and published by the IRIS Instrumentation Committee and GSNSC. Based on these specifications, we have begun procuring and testing potential prototype sensors. With a significant contribution from the DOE, the USGS and IRIS are beginning the procurement process for a large number of primary sensors and plan to begin installing these during the performance period of the proposed Cooperative Agreement. Replacing the entire GSN primary sensor suite will require ~$10M in capitalization and additional funding for deployment. The DOE has contributed nearly half of these funds for the initial investment and the remaining capitalization funds will continue to be sought from other organizations benefiting from the GSN facility. Deployment of the next-generation primary sensors will be incorporated within the basic station O&M of the GSN (core costs).


Figure GSN-5. The high-quality operations of the GSN owes its success to the dedicated staff at the USGS Albuquerque Seismological Laboratory (above) and at UCSD Project IDA (right).

3.1.4.4. GEOPHYSICAL OBSERVATORIES

As a global observatory with real-time data communication, the GSN provides a unique platform for other types of geophysical observations. The GSN has encouraged the installation of auxiliary geophysical sensors as a part of the station infrastructure support system. This has allowed the colocated measurement of ancillary signals to not only take advantage of the GSN platform, but also to enhance the data set with related nonseismic measurements. These sensors have included microbarographs, magnetometers, and GPS observatories, and those for weather. We propose to continue the installation of these ancillary sensors with the inclusion of infrasound arrays (adding seismo-acoustic capabilities to the GSN stations) and meteorological packages to improve weather monitoring and assist in state-of-health determination to allow the comparison of seismic noise to weather phenomenon.

3.1.4.5. COVERAGE

A GSN design goal was to establish uniform coverage of high-quality very broadband seismic stations around the globe. In order for the GSN to attain this goal, we depend on collaborations with the FDSN and ocean bottom seismometer (OBS) communities to assist in filling gaps in coverage. In particular, the current distribution of GSN stations exhibits major gaps in coverage in the ocean. However, the costs for ocean-based GSN-type stations are not realizable within the core funding of the IRIS program. There are other groups who are funded to perform OBS experiments and we would like to coordinate with these PIs and NSF's Division of Ocean Sciences (OCE) to determine the incremental costs to add GSN-type sensors and operational goals to existing experiments. There is an opportunity to enhance our communications with the Ocean Bottom Seismic Instrument Pool (OBSIP) instrument centers as IRIS is now the OBSIP Management Office, coordinated through Instrumentation Services, and separately funded by NSF OCE. With this new opportunity for coordination, we will continue engaging the OBS community in the GSN scientific needs and facilitate interchange between the OBS and GSN communities through workshops, steering committee interactions, and closer coordination with NSF OCE managers. We propose a modest level of funding to facilitate this interaction and to provide seed funds for incremental GSN expansion to an existing experiment.

In addition, continued efforts related to coordination and collaboration with the FDSN backbone community will be important to continue the encouragement of the open data sharing model and high data quality standards set by the GSN.

3.1.5. POLAR SUPPORT SERVICES

Seismology provides unique and diverse contributions to geophysical and environmental studies of polar regions. Applying similar methodologies to those used by projects in more temperate regions, polar seismological studies advance understanding of the structure and evolution of Antarctica and the ocean-to-continent transitions in the Arctic. Polar seismological studies contribute to research on the essential components of ice sheet formation and glacial isostatic adjustment processes in presently and recently glaciated continental regions by helping to constrain key properties such as the elastic thickness of the lithosphere, geothermal heat flow, locations of hidden tectonic boundaries, and the viscosity of the underlying mantle (Barklage et al., 2009). Seismological observations near the pole of rotation are essential for interpreting core structure and its influence on the generation of Earth's magnetic field (Song and Dai, 2008). Seismology is also an important tool for glaciologists in studies of ice structure and dynamics at all scales (Nettles and Ekström, 2012).

In support of these research activities, IRIS involvement in polar regions has progressed from the early installation of GSN permanent stations in the 1980s, to limited use of PI-adapted PASSCAL equipment for pioneering crustal and mantle studies in the 1990s, to recent development and deployment of specialized cold-hardened, high-latitude systems for a rapidly expanding number of applications in geophysics and glaciology. With the enhanced capabilities IRIS has developed in the polar regions, new doors are being opened for studying seismological phenomena associated with the changing cryosphere, including englacial and calving-related glacial earthquakes, interaction processes between oceans and ice shelves, and sub-ice volcanic and tectonic seismicity. As such, the gap between the traditional GSN and PASSCAL bounds has been bridged; we now have the capability to operate permanent regional- to local-scale observatories on any landmass around the planet, including the most remote areas where unattended stations were previously infeasible.

These greatly increased IRIS activities in the development and use of seismological facilities for polar studies have been made possible with supplemental funding from NSF's Antarctic Division of the Office of Polar Programs (OPP). The activities in this section, and the request for Polar Support Services (PSS) in the accompanying budget, are included in this proposal to show the integration of these activities under IRIS Instrumentation Services. In the past, funding has been provided separately by OPP through an internal NSF fund transfer and included under a single, integrated NSF Cooperative Agreement, and we expect this structure to continue.

Table PSS-1. Polar equipment pool. Portable polar experiments also leverage the general IRIS portable pool in more temperate areas.

Polar equipment	#
Quanterra Q330	51
Triaxial Broadband sensors (≥ 120 sec)	75
Intermediate Period Triaxial sensors	6
Snow Streamers for active source sensors	9

Description of the Polar Facility

With the increased interest in the study of polar environments, IRIS has developed capabilities that have allowed seismologists and glaciologists to acquire year-round seismic data from study areas that were previously out of reach. Over the past 10 years, NSF OPP has made a large investment in the expansion of these capabilities at IRIS. Through Major Research Instrumentation (MRI) awards for development and acquisition, and in collaboration with partner organizations (particularly UNAVCO), IRIS has successfully designed and developed smaller, lighter, and more robust observatory platforms that have facilitated high rates of data return from experiments in the most remote and extreme parts of the Arctic and Antarctic.

IRIS presently supports approximately 70 new portable experiments per year worldwide, with ~20% of these experiments focusing on polar regions. Polar projects commonly require an incremental level of support beyond the standard level provided to all portable experiments. Specialized polar support allows for developing cold-related engineering solutions, equipment fabrication and preparation for extreme conditions, and enhanced and extended field support. The Polar Support Services staff focuses on:

- Developing successful cold-station deployment strategies
- Collaborating with vendors to develop and test cold-rated seismic and associated equipment
- Integrating components into robust and complete field-deployable systems
- Maintaining a pool of cold-hardened seismic equipment components for use by the broad PI community
- Building an engineering exchange with UNAVCO for development and experiment support
- Creating an open-resource repository for cold-station techniques and test data for seismologists and others in the polar science community

In just the past five years, typical data recovery rates from year-round, unattended observations have increased from < 50% to > 90%, largely due to the development of a winter data collecting capability. With data collection and scientific successes shown in the wide-ranging AGAP/GAMSEIS and POLENET/ANET International Polar Year experiments (located in East and West Antarctica, respectively), there is growing interest in expanding such projects and in generally enhancing sustained observations near Earth's poles, including observations of changing glacial systems.

IRIS' founding principles are not only related to the collection and distribution of seismological data, but also to the education of the seismological community. As we improve our capabilities in polar regions, we can offer education and engineering support to national and international colleagues in successful deployments of polar seismological and other experiments. IRIS currently provides resources in the form of online documentation and consultation to other science disciplines such as climatology, glaciology, and physics. In addition, IRIS sees the need to be proactive in sharing information with the broader scientific community. In 2010, IRIS facilitated an NSF OPP-funded workshop on autonomous polar observing systems (APOS; Wiens et al., 2011) that brought together members of a broad scientific community to advance more robust remote autonomous observations across a variety of field (e.g., seismology, geodesy, geomagnetics, atmospherics, space physics,). IRIS and UNAVCO have collaborated to advance remote autonomous station design for polar environments and have shared success stories and best practices during interchange with groups from other disciplines in targeted technical meetings such as the annual Polar Technology Conference as well as through major scientific meetings.

With sustained core support, IRIS PSS will be able to continue incremental development efforts for improved cold region systems as part of ongoing field support.

Scientific Justification

Glaciology. The response of glaciers and ice sheets to climate change is critically important, but poorly understood. Climate change affects ice sheets, which in turn affect climate, and ice discharge from major glaciers makes a significant contribution to sea level change and to ocean circulation patterns. Variations in glacier flow speed (over timescales from minutes to years) lead to large internal deformations that include dynamic thinning of the ice. Understanding the physical controls on ice stream and outlet-glacier flow, and the time scales of response to climatic forcing, is necessary to properly model the transfer of freshwater from the polar ice caps to the world ocean.

From a seismology perspective, glacial processes relevant to the interplay among ice, climate, and sea level rise generate seismic signals. These seismic signals (both impulsive events and emergent tremor) are associated with internal deformation of the ice in response to gravitational driving stresses and the sliding of ice across a basal substratum influenced by subglacial hydrology, including the drainage of supraglacial lakes into englacial and subglacial conduits. Additional seismic signals are generated by processes at the ice-ocean interface, such as ice shelf disintegration and the calving, collision, and capsizing of icebergs. All of these processes are integral to the overall dynamics of glaciers, and seismic observations of their signals thus provide a quantitative means for both understanding the processes and for monitoring changes in their behavior. To record these seismic signals, it is necessary to supplement the observations from global distances (thousands of kilometers away) with higher resolution data from regional (< 1000 km) and local (< 10 km) distances. Long-term seismic monitoring of ice sheets can contribute to identifying possible mechanisms and metrics relevant to ice sheet collapse or other dynamic behavior, and will provide new constraints on ice sheet dynamic processes and their potential roles in sea level rise during the coming decades. In addition, higher-resolution seismic studies using active-source instrumentation can help define the subglacial topography to better understand basal ice-rock interactions.

Solid Earth Structure, Tectonics, and Ice Sheet Stability. Antarctica and Greenland constitute key regions where Earth's major ice sheets interact with both ongoing geodynamic processes and inherited tectonic features. However, the geological, geophysical, and tectonic history of these regions is poorly understood. This is partially due to the fact that geological samples are difficult to obtain because of ice coverage, but also because of the limited history of seismic deployments resulting from the lack of specialized equipment.

The relevance of solid Earth structure and tectonics to ice sheet dynamics and sea level rise is clear. 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). Understanding of glacial isostatic adjustment is required in

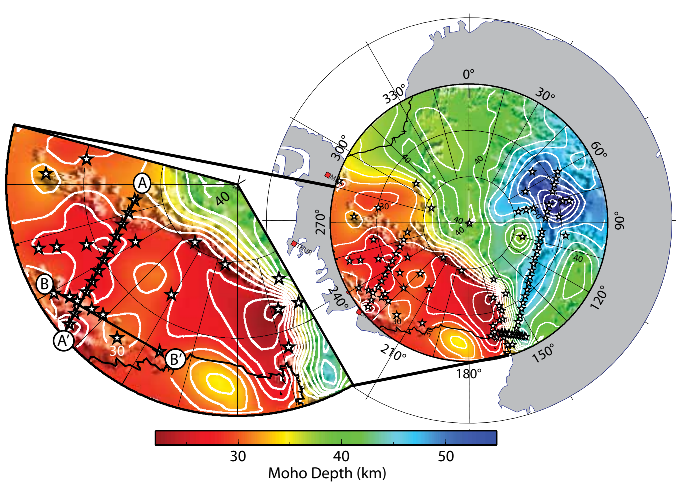


Figure PSS-1. Large-scale IRIS-supported portable broadband experiments deployed in Antarctica, with stations indicated by stars. Projects include the pioneering TAMSEIS (2000–2002), AGAP (2008–2011) (East Antarctica), and POLENET (2008–present) (West Antarctica). The underlying map shows crustal thickness derived jointly from ambient noise surface wave (Sun et al., 2011; Hansen, et al., 2009) and receiver function constraints (Chaput et al., 2012) using data from these deployments.

order to estimate the present-day ice mass loss from satellite observations such as GRACE (e.g., Whitehouse et al., 2012). Coupled ice-sheet climate models (e.g., DeConto et al., 2012) require estimates of sediment thickness at the base of the ice sheet, which can lubricate the ice-rock interface. In particular, high heat flow could produce sub-ice water that reduces bed friction, and may lead to the formation of subglacial lakes. Obtaining new seismic data is critical for advancing our knowledge of solid Earth structure and tectonics in polar regions and consequently vital to understanding ice sheet stability and sea level rise.

Deep Earth Structure. Global observatories in the polar regions, at best, provide sparse coverage for the study of axial symmetric properties of Earth. With only five GSN stations in Antarctica and eight to 10 in the Arctic, there are significant gaps in coverage for high-resolution studies of deep Earth structure in the polar regions. Although our international colleagues operate a few seismic stations around the poles, very few have data offered in real time, and all are colocated with scientific bases, many of them coastal, that are subjected to increased background noise contamination from human sources and ocean-land interactions. With recent developments in remote, autonomous seismological observatories (funded by NSF through IRIS core, the Greenland Ice Sheet Monitoring Network, OPP, and the USGS), we have observed that moving away from scientific bases and coastal areas allows for phenomenal reduction in noise levels in seismic data, thus allowing substantial increases in the quality and quantity of signals that can be observed in these sparsely covered areas of the globe. This greatly enhances the value of data returned from these logistically expensive stations.

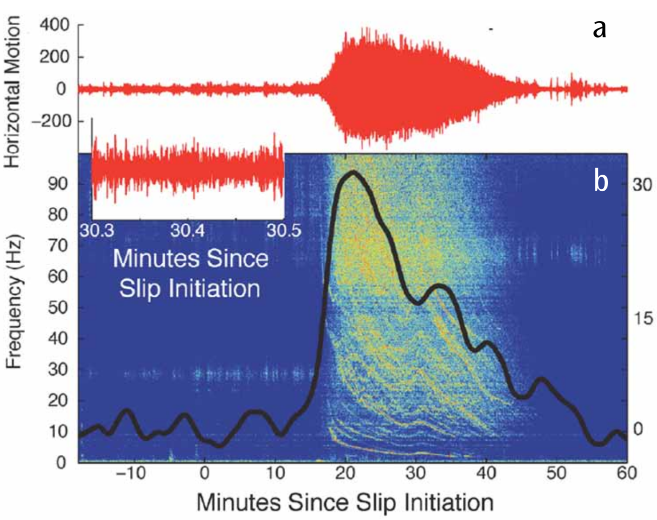


Figure PSS-2. Tremor associated with the slip of the Whillans Ice Stream, West Antarctica, as recorded by IRIS polar instrumentation (Winberry et al., submitted). Twice-daily slip events of a ~ 100 x 150 km region just upstream of the grounding line of the Whillans Ice Stream radiate teleseismic energy (Wiens et al., 2008). (a) Seismographs deployed on the ice stream shows that each slip event is accompanied by seismic tremor. (b) The slip velocity from GPS (black) and tremor spectra show harmonic spectral lines demonstrating "gliding" phenomena as their frequency changes proportional to slip velocity. Close examination of the seismograms reveals that the tremor is made up of many repeating microearthquakes, representing the repeated rupture of small asperities at the ice stream bed. The repeat rate changes as the slip velocity varies, producing the tremor spectral bands. Such studies provide a link between glaciology and the study of the physics of faulting.

Long-Term Vision for the Polar Facility

Operating seismological observatories in the extreme polar environments requires highly specialized instrumentation and trained personnel to design and fabricate this equipment, and to deploy it under harsh conditions. Operation of seismological observatories under these conditions requires advancing the capabilities of the IRIS facility above and beyond typical requirements currently supported by the portable and permanent observatory programs (PASSCAL and GSN, respectively). Therefore, we seek to continue to augment core IRIS programs with incremental support for operations, design, and maintenance of the specialized polar equipment, as well to sustain the engineering expertise that IRIS has developed through prior OPP support.

A workshop was held in the fall of 2011 that brought together representatives from the polar seismic and geodetic PI community, IRIS and UNAVCO facilities, and NSF OPP to establish a community-based long-range plan for the IRIS and UNAVCO polar facilities. The recommendations made at this workshop are presented in *A Facility Plan for Polar Seismic and Geodetic Science: Meeting Community Needs Through UNAVCO and IRIS Polar Services* (PNSC, 2012) which received broad input from the workshop participants and other members of the IRIS and UNAVCO communities. The goal of this plan is to help provide guidance and recommendations for the maintenance and growth of the capabilities within these two NSF facilities to support the growing needs of science observations in polar regions. The activities proposed here are directly tied to recommendations put forth in this polar facility plan (PFP).

Proposed Activities

A dedicated, experienced, and well-trained staff that can focus on the unique requirements of polar experiments is a critical element in maintaining IRIS's contributions to Arctic and Antarctic studies and to sustain the investments NSF has previously made in enhanced Polar Support Services. A core group of polar-dedicated FTEs allows IRIS to sustain a commitment to polar design and transform field experiments by reducing logistics requirements, optimizing field deployments, and increasing data returns. Operating in a truly bipolar sense, PSS staff are busy year-round in the direct support of Arctic and Antarctic field deployments, field season preparations, field season planning; engineering, fabrication, and development activities, and management of various PI experiment requirements (which can be highly specialized). Polar personnel-support elements are distributed among all the following proposed activities, along with the other costs associated with maintaining current capabilities and assuring that there is community involvement and guidance for the facility.

3.1.5.1. MANAGEMENT

Management activities associated with PSS are driven by the coordination of activities across the IRIS Instrumentation Services Directorate; with UNAVCO; with NSF (both OPP and EAR); with PIs and science teams; and with the community governance structures. This broad coordination, and the complex logistics of working in polar regions, require significant technical and operational oversight and management. The recent PFP (PNSC, 2012) under development for NSF includes recommendations for improving polar facility management and IRIS intends to work with the community and NSF to implement changes required to assure that the facility, community, and NSF are all represented and the lines of communication are clear. To coordinate current polar activities, and especially to develop and expand PSS activities in technology development and field support, IRIS is prepared to establish a position fully dedicated to management of PSS. The funding guidelines provided by OPP for this proposal, however, are insufficient to support a full-time position. IRIS will continue to work with OPP to explore ways in which this support level might be increased. In the meantime, the tasks of Polar Management will be coordinated and delegated through the IRIS Instrumentation Services team, closely coupled with the management of the PSS team at the PASSCAL Instrument Center. A single point of contact will be identified to interact with the community and NSF and to represent the PSS at the Polar Network Science Committee (PNSC) and other program committee meetings and at the IRIS Board of Directors meetings.

3.1.5.2. GOVERNANCE

The polar community is represented through the joint IRIS/UNAVCO PNSC. Four members of the PNSC (including a seismology co-chair) are selected by the IRIS Board of Directors to represent the seismology community's interest in the polar regions, and these four members provide guidance to IRIS PSS on the size and makeup of the polar instrumentation pool, support requirements for PI experiments, specialized data handling, and telemetry needs. They also look to the future for engineering developments required to meet new polar challenges. Within IRIS Instrumentation Services, PSS activities are most closely tied to Portable Seismology and PSS interests currently are represented through PASSCAL Standing Committee, which provides the conduit to the Board of Directors. The seismology co-chair of the PNSC is a participant in the standing committee meetings and is invited to attend Board meetings, as necessary. The community has made recommendations in the PFP for enhanced governance within IRIS to improve efficient, effective, and transparent input from the community to PSS and to increase budget oversight. As discussed in the earlier section on IRIS Governance and Management, the IRIS Board is reviewing the current governance IRIS structure and PFP recommendations will be included in this process as changes are implemented over the next year.

Figure PSS-3. Mt Paterson, Antarctica: Joint IRIS/UNAVCO POLENET station in Antarctica.

3.1.5.3. OPERATIONS

Polar Pool Instrumentation. Through OPP supplemental funding and NSF MRI acquisition awards, IRIS PSS has established a pool of specialized, cold-rated instrumentation to be used for temporary experiments in the polar regions. The operating environment in the polar regions would put normal PASSCAL-type equipment far beyond the manufacturers specifications for low-temperature operations. We have worked with several vendors to lower these operating specifications, but have also had to improve the environmental controls to keep all systems running in ambient temperatures that can reach −80°C. In addition, power and communications systems need to be altered and redesigned for high latitudes, low temperatures, and extended periods of low-to-no sunlight operations. The pool requires personnel and facility resources to maintain the equipment in operating condition, perform integration of new equipment into the pool, perform cold testing of complete systems and storage, and to pack and ship equipment to remote locations. Maintenance of the pool will require occasional repairs and replacement of items to ensure the pool numbers remain constant. It is understood from NSF OPP that substantial growth of the pool should not be funded under the core IRIS proposal, but should come from supplemental proposals (experiment-specific) or additional acquisition MRI proposals. That said, it is clear from the PFP that the polar community wishes to increase the pool's size, including adding a broader range of sensors, and enhance power systems and improve telemetry. We will continue to pursue pool growth through separate proposals.

PI Support. Once seasonal plans for supported experiments are received from NSF OPP, the PSS staff at IRIS begins working with PIs to capture experiment-specific needs for pool equipment, environment, and operation specifications and to establish plans for integration, testing, packaging, shipping, and deployment/field support. If resources are required beyond the capabilities of the existing pool, the PSS staff will work with the Polar Manager to request supplemental equipment, materials, and supplies from NSF OPP. Most of the generic requirements are identified in the proposal stage, but actual needs are clarified once the awards are in place and field plans are finalized. In addition to experiment-specific support, more general polar PI support includes training on deployments, software, and data handling, and logistics and field support, as necessary. Field support for polar activities leverages the core PASSCAL field engineering staff to cover intensive field seasons for short time periods.

Data. Although core PASSCAL services provide general data handling, there are specific data handling requirements for polar experiments, as the communications topology is substantially different. Primarily, this involves the monitoring of state-of-health (SOH) information through the Iridium telemetry links and coordination with PIs and field support for remote maintenance and field planning for follow-on seasons. When there are real-time telemetry links, PSS staff provide network monitoring of remote stations, metadata upkeep, SOH monitoring, data quality control, and software engineering support required for the telemetry systems.

Engineering and Technology Development. To maintain an innovative Polar station pool, IRIS will continue to pursue incremental development and modifications to the existing station, communications, and power-system designs. Battery technologies are continually evolving and will likely continue to surge in design innovation over the next several years. Although the current polar station power system design is effective and compact, its cost is high. Having knowledgeable PSS staff to design new systems, and test and adapt emerging battery technologies for cold-weather applications, will be essential to ensure that the most cost-effective technologies are implemented. Like battery technologies, high-latitude communications are quickly evolving. The current polar station design has a solution for SOH communications based on the relatively expensive and limited bandwidth of current low-Earth-orbit polar satellite systems. However, our science community continually stresses the need for real-time full-bandwidth data return, and solutions can be anticipated in the near future as communications systems evolve. With better communications and advanced battery technologies, we could truly approach the goal of robust, infrequently visited autonomous stations, thus reducing long-term logistics costs.

Because power and telemetry designs are common to all remote autonomous observing systems in the polar regions, we will continue to interact with the broader polar community, in particular, our UNAVCO partners as well as the other participants in the PFP, to ensure that efficient design technology is shared and made available to the global science community. Recent activities show that this strategy is advancing; beginning with a collaborative design MRI between IRIS and UNAVCO on remote autonomous station design, efforts have expanded to the broader scientific observing community through the APOS workshop in 2010, the PFP in 2011, and within the annual Polar Technology Conferences.

IRIS/UNAVCO Collaborations on Polar Efforts

IRIS and UNAVCO have supported a collaborative effort on remote polar station design and technology development, successfully completing an engineering effort (MRI funded by the NSF Office of Polar Programs) to engineer a standardized, scalable, remote power and communications system that allows for robust recording of seismic (IRIS) and geodetic (UNAVCO) data in the harsh Antarctic environment. The funds were used to develop cold hardened enclosures that integrate primary and secondary power systems with cold rated switching electronics, wind- and cold-hardened structures for solar panel mounts, and a communications interface using Iridium satellites. These systems are capable of running continuously through the long periods of polar darkness. Techniques have been established for the installation of these systems to ensure high levels of survivability and data return.

Using these designs, UNAVCO and IRIS participated in the POLENET experiment that colocated seismic and geodetic equipment throughout western Antarctica in the large, continental-scale demonstration of the new capabilities for these NSF facilities. Coordinating and sharing logistics support from the United States Antarctic Program demonstrate how the collaborative activities helped to optimize the logistics resources during this large experiment.

Both facilities participated in the Autonomous Polar Observing Systems workshop to share these collaborative designs with the broader science community and annually exchange ideas during the Polar Technology Conferences. Recently, both facilities worked with the polar seismic and geodetic community to develop a Polar Facility Plan to help define the facility capabilities to meet the science needs in the polar regions.

IRIS and UNAVCO have continued to work well together to exchange information, design, and logistics information to help improve scientific return while working optimally within the constraints of NSF's polar resources.

Developed jointly by UNAVCO and IRIS.

Joint IRIS/UNAVCO collaboration on a remote autonomous seismic/geodetic station in Greenland (DYE2G - Raven Camp, Greenland). Photo by Dean Childs.

3.1.6. TRANSPORTABLE ARRAY

In less than a decade, data produced by the USArray Transportable Array have transformed the scale and detail at which the structure and deformation of a continent has been imaged and understood. The uniformly spaced and geographically expansive array of high-quality observations has enabled researchers from the United States and around the world to use new and existing tools, such as ambient noise tomography, travel-time tomography, receiver functions, and shear wave splitting measurements to study continental assembly, structure, and evolution at unprecedented scales and resolution. Further, it is the first seismic network to probe every corner of the country, bringing closer the fields of geology and seismology. As a continental-scale array, the TA has also provided unique new views into all parts of the planet, including the structure of the deep Earth and high-resolution images of the rupture process during great earthquakes. Results from analyses of TA data are presented in numerous peer-reviewed publications each year, and are already being used in many Earth science textbooks.

At present, the TA consists of ~450 stations operated in a uniform, wide-aperture array (Figure TA-1). Each station contains a three-component broadband seismometer that records a wide range of seismic signals. Stations also monitor various state-of-health parameters and are equipped with an infrasound microphone and barometer that record a similarly broadband spectrum of atmospheric pressure signals that are produced by, among other things, bolide air bursts and severe weather. The seismometer and complementary hardware are buried in a subsurface vault that has been carefully designed to minimize noise by providing high thermal insulation, while at the same time incorporating standardization and ease of installation. External solar panels that charge batteries provide power, enabling the station to operate continuously and autonomously. The solar panel mast also supports a GPS receiver and cellular/radio modem for precise timing and continuous real-time telemetry.

TA station installation began in California in the fall of 2004. The TA completed its first 400 station footprint in 2007, spanning the entire western United States. Since then, the TA has rolled eastward at a rate of ~18 stations per month year-round. Crews at the front of the array construct stations and install instruments, while crews at the rear decommission the sites.

Since its inception, the TA has maintained a high standard for quantity and quality of data returned. Telemetry gaps from TA stations are rare, and the real-time data return for stations is above 99%, well above NSF's EarthScope performance metric of 85%. This performance is due, in part, to the uniformity of the design, construction, and installation of TA stations. Some station design aspects have evolved, for example, the vault (tank) materials were modified to suit the changing field conditions in eastern North America, making the station more resistant to flooding from shallower water tables. This proposal anticipates further design changes to the station enclosure, sensor emplacement, and data communications to support TA station operation in the Alaska and Yukon environment.

TA operations are organized into distinct subcomponents overseen by the Transportable Array Manager. This structure has proven to be effective in both USArray and IRIS core operations. The Array Operations Facility (AOF), operated through a subaward to NMT, supports the TA deployment by warehousing equipment, repairing hardware, and shipping instruments and other associated station materials. Station construction, installation, and removal are handled by contracted field crews. The Array Network Facility (ANF), operated through a subaward to UCSD, tracks the overall TA communications network, monitors and evaluates station quality, and assembles essential metadata that describe the station sensors. Data and metadata are routed immediately from the ANF to the IRIS DMC, which (as a separate proposal task) is responsible for the long-term archive and distribution of TA data to the scientific community and the public.

TA stations are also operated outside of the current footprint as part of the Cascadia Initiative and as contributing stations to the USArray Reference Network (RefNet). The Cascadia Initiative is an NSF-initiated effort to create an integrated

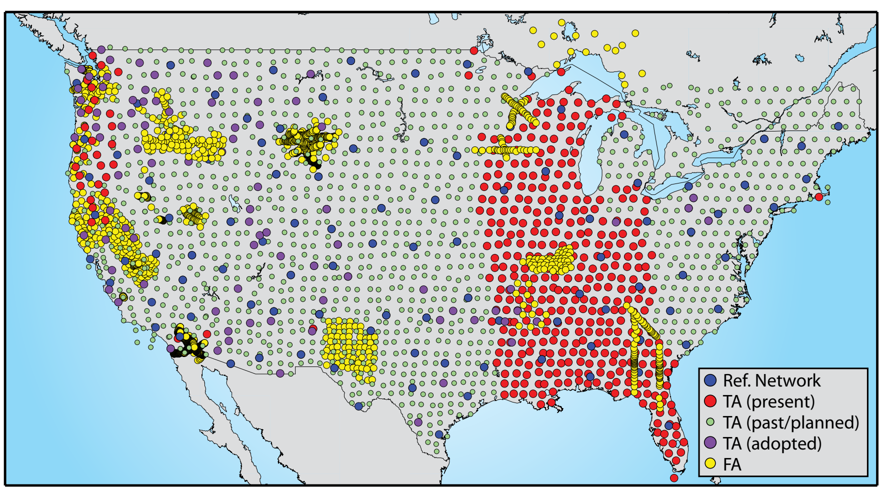


Figure TA-1. USArray stations spanning North America. The current (August 2012) TA footprint in the central and eastern United States (red symbols) is flanked by past TA station sites in the west and planned stations to the east (green). All planned sites will be completed by September 2013. PI-driven FA experiments (yellow symbols) have leveraged the presence of the migrating TA. Adopted TA stations (purple symbols) are a similar leveraging of the TA by regional network operators. The Reference Network provides a consistent backbone for both the TA and FA.

onshore-offshore observing capability, and includes 27 TA stations installed along the Pacific Coast, from Canada to Northern California (other NSF-supported elements include ocean bottom seismometers deployed offshore, and high-rate real-time PBO GPS stations). The RefNet is a virtual network of ~100 stations across the contiguous United States that provides a fixed reference frame for the mobile TA. RefNet stations are spaced at intervals of 300 km, and are operated by the USGS (directly or via regional network operators) as part of the Advanced National Seismic System backbone. The TA added 20 stations to RefNet at locations that enhance the uniformity of its coverage.

IRIS offers local network operators, universities, or state agencies the opportunity to acquire fully operational TA stations (colloquially referred to as "station adoption"). The cost of station equipment is reimbursed to the USArray program to purchase replacement hardware, and IRIS offers EARN, a program in which IRIS operates the station and data flow for an annual fee. So far, over 50 complete stations have been acquired in this manner and continue to provide high-quality, open data to the seismological community.

Installation of the Central and Eastern US Network. The President's FY13 federal budget proposes support for a large-scale program to retain TA stations in the central and eastern United States as a result of a coordinated, collaborative effort among multiple government agencies and the Office of Science Technology Policy. The intent of this program is to create a Central and Eastern US Network (CEUSN) by extending the observational period of 200 or more TA stations for five years to provide data critical to addressing both seismic hazard in the central and eastern United States as well as basic research questions in this region and beyond. The potential value of "leaving behind" operating some TA stations in-place in this region for longer time periods stations was reinforced by the 2011 Mineral, VA, earthquake and the recent observed increase in low-level seismicity related to wastewater injection related to hydraulic fracturing. TA stations provide a cost-effective way to address long term, multiagency needs as the stations are already in place and operating. As outlined in the FY13 budget, NSF will be funded to support the CEUSN from FY13–FY17. A committee representing federal, state, and university interests has prepared a prioritized list of stations to be retained, that best augment existing facilities and optimize multiple observing objectives. The operation of this TA legacy network, while not part of this proposal, may provide an opportunity to replace sensor equipment with models suitable to Alaska (discussed further below).

Scientific Justification

Already a number of special sessions at major national science conferences and workshops have been devoted to the advances in understanding Earth's structure that have been enabled by TA data, and the peer-reviewed literature is documenting these findings. As the TA rolls across North America, it is revealing the structure of the continent in new detail (Figures TA-2 and -3). P and S receiver functions (e.g., Levander et al., 2011) are illuminating the crust and lithosphere, and fueling the discussion about the nature of the lithosphere-asthenosphere boundary and features such as the Yellowstone hotspot (Kerr, 2009). The Moho depth is being mapped with unprecedented uniformity (e.g., Gilbert, 2012). Surface wave-based techniques are mapping the 3D structure of the crust and upper mantle using unaliased surface wave amplitude and velocity fields across the continent (e.g., Yang et al., 2008). The vastly improved coverage of shear wave splitting measurements (West et al., 2009) are using upper mantle anisotropy to reveal dynamic processes under North America. And in Cascadia, TA stations are contributing to mapping the spatial and temporal patterns of tectonic tremor (Boyarko and Brudzinski, 2010).

Source studies have also benefitted from TA data. As it migrates, the TA has significantly lowered the magnitude threshold of detectable seismicity (Astiz et al., 2012). Detailed reanalysis of TA data across specific regions has yielded regionally complete catalogs to M1.2, and detection of events as small as M0.0 (e.g., Lockridge et al., 2012, for Arizona). Advance of the TA into the seismically undersampled eastern United States provides an opportunity for increasing understanding of how continents form and then rift apart (Wolin et al., 2012). While rare, large earthquakes do occur in the East, and the opportunity to observe seismic wave attenuation and propagation with a dense, high-quality array is valuable for

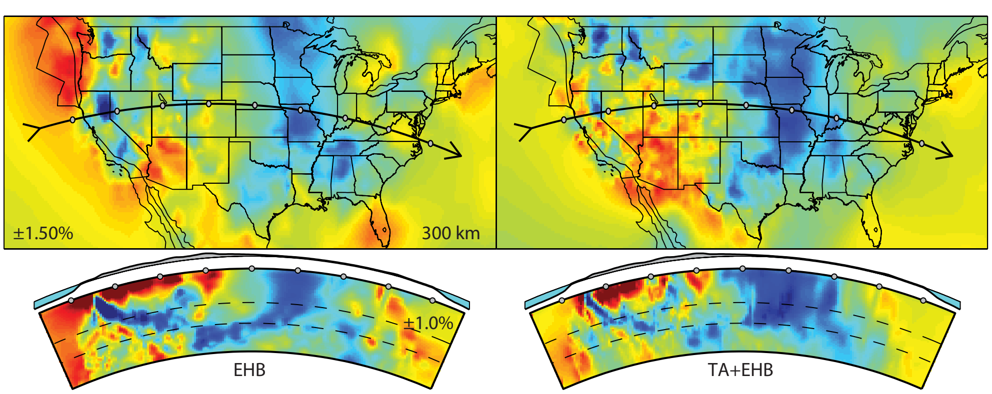


Figure TA-2. Tomographic models of P wave speed before and after TA deployment. Comparison shows map view at 300 km depth and a vertical profile from 0–1000 km depth. The model on the left uses only EHB catalog data. The model on the right also incorporates data from TA stations through May 2011, which includes sites from the Pacific coast to ~91°W (i.e., roughly the north-south line from Minnesota to Louisiana). The comparison clearly demonstrates the increased resolving power produced by the use of TA data. *(Models courtesy of Scott Burdick; see Burdick, et al., 2010, for details.)*

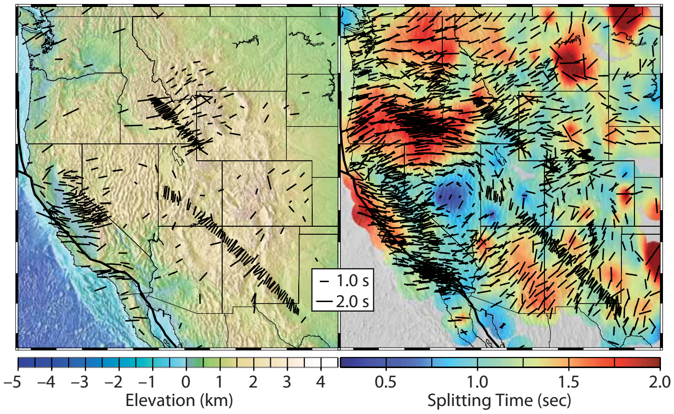


Figure TA-3. Pre- and post-EarthScope compilation of SKS splitting measurements for the western United States. (left) The irregular distribution of measurements makes it difficult to discern the full pattern and magnitude of upper mantle anisotropy. (right) Splitting measurements and contoured splitting times after deployment of the TA and FA experiments, clearly revealing the large-scale pattern of anisotropy beneath western North America. *(Figure courtesy of Matt Fouch)*

addressing a range of geological, geophysical, and engineering questions. The presence of high-quality seismometers in a region of increased shale-gas exploitation will provide new data to explore the relationship between hydraulic fracturing, disposal wells, and earthquake activity.

TA data are also used to study Earth structure and seismicity outside of North America. The TA has proven to be a powerful tool for illuminating how distant, large earthquakes rupture, using back-projection of teleseismic P-wave arrivals (e.g., Lay et al., 2010; Wang and Mori, 2011). As the TA moves eastward, this technique becomes more applicable to events in the Mediterranean and Africa. Deployment of the TA in Alaska will provide a new azimuthal perspective for major locations of seismicity across the Pacific Ocean. Simultaneous operation of Alaska and CEUSN is an especially exciting binocular view. TA targets for deep Earth structure outside of North America include the lower mantle (e.g., Sun and Helmberger, 2008) to the core-mantle boundary (e.g., Sun et al., 2010), and upper mantle discontinuities beneath South America and surrounding oceans (Schmerr and Garnero, 2007).

The TA looks upwards, as well as down, and the infrasound and barometric pressure sensors that are now part of the TA are being used to understand the structure of the atmosphere and exotic atmospheric sources such as tornadoes (Tytell et al., 2011), and gravity waves (Hedlin et al., 2011). Even before these sensors were added to the USArray, the acoustic-to-seismic converted energy recorded by the TA's seismometers was enabling unprecedented observations of the azimuthal and distance dependence of acoustic energy propagation in the Earth's atmosphere, providing observations the could finally directly corroborate modeling results (Hedlin, et al, 2010; Walker et al., 2011).

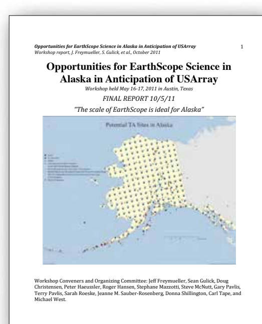
The broader scientific return from the TA's deployment in Alaska will encompass the types of studies described above and much more. The science possibilities resulting from the proposed deployment to Alaska were discussed extensively at the EarthScope planning workshop (see box below) and were a significant factor in the choice of Alaska as a GeoPRISMS primary study site (Freymueller et al., 2011b).

Opportunities for EarthScope Science in Alaska in Anticipation of USArray: A Planning Workshop Held May 16–17, 2011 in Austin, TX

Alaska has a high rate of seismic activity and active volcanism, and plays a critical role in understanding basic Earth processes such as subduction. Yet seismometers have only been deployed in a few select areas of Alaska. The spatially unaliased view provided by the TA in Alaska will reveal never-before-seen structure. Further, because the rate of Alaskan seismicity is higher than in any other US region, so the TA will capture earthquake activity on a nearly continuous basis. An Alaska EarthScope workshop report and accompanying white papers provide the overarching vision for the key scientific targets that can be addressed via the combined presence of the TA and PBO GPS stations in Alaska. Some primary research targets include:

- Delineating the presence and role of relic slabs and arcs
- Studying strike-slip boundaries as lithospheric-scale structures
- Examining mantle flow around slab edges
- Contrasting differences between oceanic and continental arcs
- Identifying the causes of earthquake rupture segments and the boundaries between them
- Examining the lithospheric process of flat-slab subduction
- Understanding terrane accretion and far-field deformation
- Determining relationships between seismicity and uplift

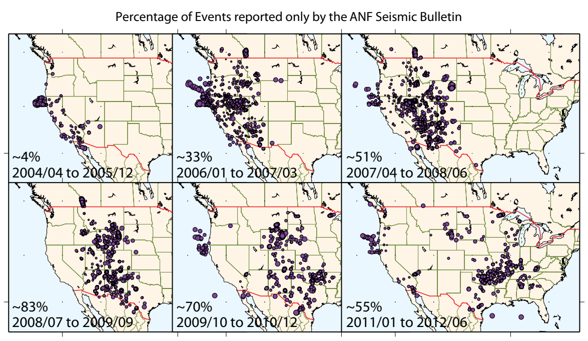
As in the lower-48, we anticipate that the TA will stimulate higher-resolution FA experiments that leverage the TA as a "backbone." These densely spaced deployments will operate at local and regional scales to address specific research targets, including intra-crustal-scale high-resolution structural mapping, microseismicity surveys, and higher data-fold imaging of the crust and mantle. In many cases, these experiments are expected to be conducted in partnership with NSF's GeoPRISMS program.


Opportunities for EarthScope Science in Alaska in Anticipation of USArray
FINAL REPORT 10/5/11
"The scale of EarthScope is ideal for Alaska"
Potential TA Sites in Alaska

Seventy-six people attended a 2011 workshop addressing EarthScope science goals for Alaska, and also TA deployment strategies and priorities. The TA deployment plans presented in this proposal are based on plans presented, refined, and endorsed at this workshop and in response to the science objectives. For full report, see Freymueller et al. (2011a).

Earthquakes in the Central and Eastern United States

Information about seismicity from the Transportable Array is especially important in the central and eastern United States, where monitoring networks are sparser than in the West and where smaller earthquakes are important for characterizing faults and deformation produce earthquake that are infrequent but nevertheless occasionally very damaging. These data enhance understanding of tectonic events within the stable continent as well as human-induced events, as demonstrated in 2011 with the Arkansas earthquake swarm that culminated in a 4.7 event on 27 February, the 5.8 Virginia earthquake on 23 August, the 5.6 Oklahoma earthquake on 5 November, the 4.8 southern Texas earthquake on 20 October, and the 4.0 Ohio earthquake on 31 December.



Among hypocenters computed by the Array Network Facility, the proportion that are not found in any other catalogs is small in the West where many permanent stations provide coverage, but is dramatically greater further east. *(Courtesy of Luciana Astiz)*

Proposed Activities

Completion of the Lower-48 and Deployment to Alaska. The TA will complete installations in the lower-48 states and eastern Canada by September 2013. IRIS proposes to operate the stations in the lower-48 TA through 2015, removing stations from west to east at the current rate of ~18 per month. The removed equipment will be redeployed to Alaska. The 20 RefNet stations will operate through FY18 and the 27 Cascadia stations will operate until the expected completion of the offshore instruments in FY15.

The proposed deployment in Alaska includes operation of ~290 stations in a grid-like pattern with ~85 km spacing; covering all of interior Alaska and westernmost Canada. (Figure TA-4). The deployment will have a phased start in 2013 and 2014 and accelerate over the following two summers and will be completed during the summer of 2018. Each station will be installed once (i.e., the array will not "roll" as in the lower 48). Removal of the stations will commence in FY19. Although this defers the cost of demobilization to a subsequent award (post-2018), the importance of the unique TA observations in Alaska, and the significant investment in deployment, argue for maximizing the observational period for the completed array. In addition, this extended observational period (two to five years) increases the opportunity to arrange for station "adoption" and conversion to permanent operation, by organizations and agencies with special interests in Alaskan seismicity. This deployment schedule further allows for the careful planning and implementation of additional FA experiments that are anticipated to build upon the TA baseline, including the possibility of experiments that extend from the continent into the ocean.

Roughly 35 locations within the planned grid will use existing stations, which may require various levels of upgrade or support to meet TA performance goals. IRIS is working with the Alaska Regional Network, Alaska Volcano Observatory, and the Alaska Tsunami Warning Seismic System to leverage existing infrastructure, for example, upgrading the primary sensor at existing sites to include longer-period response, improving the sensor emplacement through drilling, or enabling new telemetry options. This approach has been successful in other areas with substantial existing capabilities like California as it yields long-term assets for the network and provides essential local experience to USArray.

Several steps have been taken to anticipate and meet the logistical and environmental challenges inherent to working in Alaska. The primary challenge for the TA is to achieve economical and reliable installation of seismometers in permafrost. To this end, the TA operates a test and evaluation pilot station (TOLK; Figure TA-5) at Toolik Lake Field Station, Alaska (an NSF-LTER operated by the University of Alaska Fairbanks [UAF]). TOLK was installed in summer 2011, and additional test stations are planned for deployment in 2012. The TOLK station uses auger holes with segmented PVC casing to test the isolation from frost heave during the freeze-thaw cycle. The broadband sensors are installed at 4 m

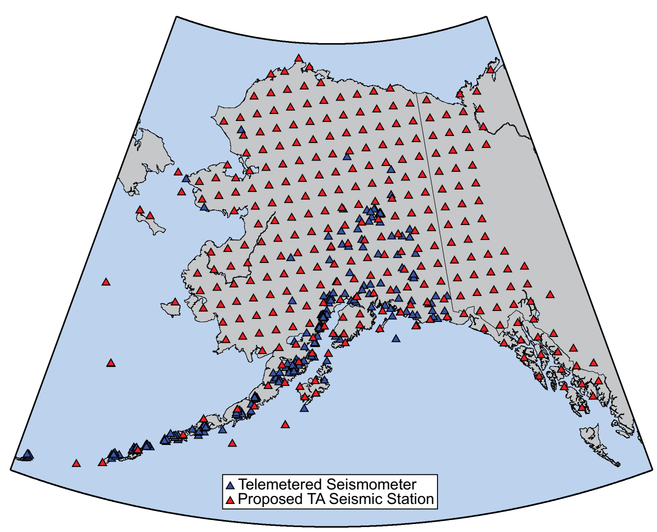


Figure TA-4. Proposed deployment of Transportable Array stations superimposed on the current real-time seismic station coverage in Alaska from various network operators.

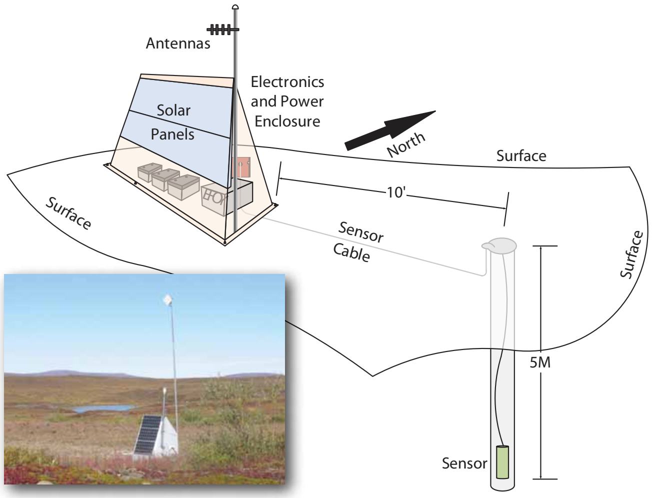


Figure TA-5. Schematic of the TA test site at Toolik Lake in Alaska and site photo.

and 5 m depth, below the unstable active layer of permafrost. These seismometers have maintained a level orientation since installation, a robust performance under these circumstances. TOLK has the best long-period horizontal noise characteristics of any station in the TA, suggesting that the scientific value of TA data collected in Alaska will be especially high.

In addition to permafrost installations, the TA is exploring the viability of new approaches for sensor emplacement in bedrock and competent (e.g., granitic) surface material. Four test instruments have been installed in boreholes at depths of 1.5 to 10 m at the USGS ASL. These sensors all exhibit improved noise performance compared to vaulted TA sensors throughout the lower-48 states.

Another challenge to station operations in Alaska is the lack of sunlight during winter when the station solar array does not supply power. To overcome this problem, the station at TOLK is testing a methanol fuel cell to charge batteries during the winter. Issues with the station design and fuel cell operation were discovered during TOLK's first winter and the design is being improved. Methanol fuel cells are only one method under consideration to enable year-round operation. More conventional approaches using air-cell primary batteries can easily support operation over two winters, and larger advanced chemistry (Lithium Iron Phosphate) batteries used in electric vehicles are now commercially available and are both lighter weight and rechargeable—allowing a large battery to coast through the winter and be recharged in summer. This approach is current practice for Alaska seismic stations, except that the necessary capacity is achieved by using ~1 ton of traditional deep-cycle lead-acid batteries per station.

Communications options in Alaska are expensive, so the real-time receipt of waveforms and metadata will be more costly and logistically difficult than in the lower-48 states. Scoping options to control costs include the amount of data transmitted, whether data are sent in near-real time or in daily increments, and whether telemetry is disabled in low-power conditions. This proposal anticipates a combination of data telemetry, primarily Ethernet radio to Internet points-of-presence and satellite terminals at stations. Communications options advance rapidly and IRIS has been nimble in adopting the most optimal and cost effective solution(s). This situation is familiar—the original plan for TA in the lower-48 (developed in 1999–2002) anticipated extensive use of satellite telemetry, whereas it is now almost entirely cell modem as a result of consumer trends in the communications industry.

During 2011–2012, IRIS contracted Honeywell Technical Services Incorporated (HTSI) to assemble a team of logisticians, civil engineers, air operations experts, and other specialists to analyze the logistics and costs associated with an Alaskan field operation, including procurement of basic supplies, staging, transportation, equipment, and construction materials. Only a fraction of stations will be deployable by road; most will be accessed via plane or helicopter. The proposed deployment model that minimizes both expense and time and maintains flexibility uses a central base of operations (e.g., Anchorage) and follows a "hub-and-spoke" model to access discrete portions of the TA footprint one area at a time (Figure TA-6). Each hub requires a landing strip (or road access) accessible by an aircraft (or truck) capable of hauling approximately 8–16 stations worth of equipment. From this staging area, helicopters will fly to stations at the ends of the spokes.

Scientific Outreach and Collaboration. The TA will continue to serve as a foundation for scientific outreach and collaboration. IRIS has already made a significant effort (e.g., meeting attendance, articles in relevant publications) to engage Arctic-focused organizations and research groups in an effort to build cross-disciplinary scientific efforts and thereby reduce mutual operational costs. For example, the UAF group engaged in soil temperature profiling to study permafrost as part of the

Figure TA-6. Hub-and-spoke deployment strategy for Alaska. Each hub is at a location accessible by road or large aircraft. The ends of the spokes are station locations.

OPP-sponsored Arctic Observing Network is eager to cooperate on deploying thermistor strings as part of the seismometer emplacement, and the NOAA branch in Alaska and the Bureau of Land Management Fairbanks district office have expressed interest in supporting weather instrumentation. The TA will deploy and operate 30 meteorological stations in Alaska, providing a strong basis for leveraging additional resources to monitor atmospheric conditions across the TA. This effort builds on the success of groups beginning to use the atmospheric data produced by the lower-48 TA (e.g., the Mesowest project at the University of Utah). NSF's involvement and engagement in these leveraging opportunities will be important. Small modifications to the TA work plan, with minimal cost impact, could yield major science returns for other (non-solid-Earth) science communities.

IRIS sustains a close relationship with the landowners and communities hosting TA facilities. The *On-Site* newsletter is sent to all landowners along with information about their particular station. Academic and public engagement, tied closely with the IRIS EPO program, continues to be a priority. This emphasis on local engagement will continue in Alaska, with a special emphasis on linkages to Native and First Nation communities. Student siting will end following the summer of 2012, with future permitting to be performed by IRIS employees or a subaward agency. Despite these changes, the TA will pursue outreach with the hosting landowners and agencies in Alaska, and establish partnerships with existing organizations involved in Arctic science outreach.

3.1.6.1. MANAGEMENT AND GOVERNANCE

The TA Manager and the Chief of Operations oversee all aspects of the TA. This includes staffing, planning, procurement, and depot and field operations. The TA is much like a high-precision manufacturing process—all parts of the process must mesh smoothly. Over the past nine years, the TA has developed a lean and efficient structure that oversees a year-round field operation and directs the choreography of personnel and equipment to allow simultaneous operations across thousands of square kilometers.

The TA Manager communicates with the other IRIS/EarthScope program managers and standing committees, and is a key participant in the Instrumentation Services management structure. The USArray/TA management team will continue to work closely with the NSF, USGS, and other outside organizations to ensure smooth permitting, deployment, and operation of the TA. With the ongoing and planned international work in Canada, it will be especially important to maintain the engagement that is already well established with the Canadian government, the sovereign First nations, and the academic community.

Close community interaction and guidance has been and will continue to be maintained through the Transportable Array Working Group, which provides advice on any issues concerning TA operation, especially those affecting science return. Most importantly, community input will guide scoping decisions if budget or performance issues arise during deployment.

3.1.6.2. EQUIPMENT/MAINTENANCE/REPAIR/REPLACEMENT

Equipment used in the TA (in Alaska, Cascadia, and RefNet) will be maintained, repaired, and replaced as necessary. New equipment suitable for deployment in Alaska will be procured, tested, and integrated. The existing AOF in New Mexico and a new facility in Alaska will provide depot services for maintenance, repair, and replacement tasks. The New Mexico-based AOF takes advantage of the experience and facilities that are used to maintain similar instruments for the Portable Seismology program (see Section 3.1.3). The Alaska AOF will be responsible for assembling equipment into forward deployment bundles and coordinating the air logistics.

As TA stations are retasked to create the CEUSN, the broadband seismometers and associated station hardware will be replaced using funds provided by the CEUSN project. This provides an opportunity to substitute instruments with ones that are more suitable for the planned design for the Alaska stations. As noted above, testing has demonstrated that auger-hole sensors and emplacements deliver excellent noise performance. Replacing part of the TA pool with "auger hole" compatible sensors will increase data quality and provide more flexible deployment options (though traditional vault-enclosed seismometers will be used in some circumstances). The current plan for the TA in Alaska assumes that the CEUSN plan is implemented as proposed, thus funding the purchase of replacement seismometers that will be used in Alaska. If the CEUSN plan is not realized, the deployment plan for Alaska will be rescoped to use existing sensors, albeit with less-optimal performance.

3.1.6.3. ARRAY OPERATIONS

Data from TA stations will be managed as at present, with the ANF collecting data, monitoring station operations, maintaining metadata, and performing quality assurance review of the data. The data and metadata will be transmitted from the ANF to the IRIS DMC for archiving and distribution. Deployed stations will have a scheduled service after two years operation and, in so far as budget allows, when warranted by lack of telemetry or improper station operation. IRIS will continue to maintain a proactive quality-control process, monitoring the integrity of incoming data streams and also the quality of the actual data and the archive available to researchers. TA station quality assessment will benefit from new quality-control metrics and tools that are being developed as part of the major thrust in Quality Assessment under this proposal (see Data Services section for more details).

As noted above, communications in Alaska are challenging, but every effort will be made to enable telemetry from every station—to provide timely delivery of data for research as well as collaboration with operational networks in Alaska, and to enable station monitoring and control (a key issue for an investment of the scale of the TA in Alaska).

The TA will continue to encourage the "adoption" of stations within its footprint by making information readily available to interested parties through the IRIS and USArray websites and outreach at community meetings, workshops, and in regular meetings with the Association of American State Geologists. Adoption of Alaskan stations is already a key discussion item with existing network operators because of the uniqueness of the opportunities provided by the TA, and the significant level of seismicity in Alaska.

Operating in Alaska: USArray and PBO Coordination

USArray and PBO will share their experience and knowledge operating in the frequently challenging conditions in Alaska to improve technical performance and decrease costs. The Polar Operations groups at UNAVCO and IRIS already collaborate extensively, and both USArray and PBO reach out to, and share information with, a variety of other groups already operating in Alaska, including network operators and PIs who have led experiments in Alaska. Some areas of technical exchange specific to USArray and PBO operations in Alaska are described below.

- *Power.* Power is a significant challenge facing PBO and USArray operations in Alaska. PBO and USArray are testing various battery types, as well as methanol fuel cells as overwinter power sources with multi-year life spans. They are also actively comparing notes on installation and operations strategies (e.g., system configuration, venting waste water, methanol transport, etc.).
- *Communications.* Real-time communications options in Alaska are costly and bandwidth and power budgets must be finely tuned. PBO is sharing results from experiments with BGAN portable satellite telemetry systems and both groups are experimenting with Iridium systems.
- *Site Selection and Permitting.* PBO's wealth of knowledge in Alaska siting and permitting is being shared with USArray via ongoing discussions with UNAVCO's permit coordinator, GPS operations manager, and regional engineer based in Anchorage. USArray has already used this information in discussions with federal and state permitting agencies and Native Corporations. PBO GPS station sites are being evaluated for compatibility with TA seismic installations, however, not all sites are compatible—due to general location and/or site characteristics.
- *Logistics.* PBO has shared insights gained via their operations in Alaska, particularly related to the efficient utilization of both helicopter and fixed wing transportation. These "lessons learned" include helicopter contracting and field support procedures. USArray has established an Alaska depot in the same facility as PBO, which should enable some shared support activities.

Developed jointly by UNAVCO and IRIS.

3.1.6.4. STATION DEPLOYMENT

All activities required to site, permit, construct, install, and remove a station are addressed as an integrated task. TA stations will be removed from the conterminous United States (~428 stations) during FY14 and FY15, with the exception of those stations that will become part of the CEUSN. TA stations will be sited, permitted, constructed, and installed in Alaska and Canada over the course of the award. As discussed in the Portable Seismology section (WBS 3.1.3), any instruments that are not required for use in Alaska or CEUSN will be made available to help sustain the inventory in the Portable Seismology instrument pool.

Permitting for TA sites in Alaska is already underway, and most stations will be positioned on state and federal land. Permitting activities will be managed by IRIS staff who will be responsible for addressing environmental, archeological and biological impacts, and engaging in consultations with native constituencies.

Construction, installation, and removal of stations will build on IRIS' extensive experience creating high-quality stations. This involves IRIS supervisory personnel, field engineers contracted through HTSI, and various contracted engineering support activities via existing network operators and experienced field hands. The transport logistics in Alaska are a new challenge. The hub-and-spoke deployment model will use helicopters to ferry equipment and personnel the last leg of travel. Thus, a large cost item in this proposal is the air logistics support. Detailed scenarios involving estimates of the weight, routes, number of sorties, optimization of to/from cargo loads, were used to build up the overall cost estimate. However, uncertainties will persist throughout the first years of installation and operation. These high costs and uncertainties are well known in existing network operations in Alaska, and IRIS has benefitted from extensive planning discussions with UAF and UNAVCO/PBO staff. Where possible, lower cost transport via road, river, or overland will be considered when that can be achieved safely.

3.1.6.5. TRANSPORTABLE ARRAY CASCADIA

The 27 TA stations installed along Cascadia as part of the Cascadia Initiative will be operated and maintained through the anticipated duration of the offshore deployments, presently set to conclude in late 2015. All aspects of station operations, data collection, management, QC, and archiving are handled the same as for the other stations of the TA. The Cascadia Initiative is supported by NSF OCE and EAR and plans for activities beyond 2015 will depend on directions (and resources) to be developed with NSF.

3.1.7. MAGNETOTELLURICS

Magnetotellurics and seismology provide complementary techniques for mapping volumetric heterogeneity within the Earth. These techniques have different sensitivities to thermal and compositional variations and the presence of fluids. Thus, the datasets from the USArray Magnetotelluric (MT), TA, and FA observatories are even more powerful when interpreted jointly. MT observations exploit the natural variations in the Earth's magnetic field caused by solar activity and lightning, which induce subsurface electrical currents. The USArray MT observatory makes orthogonal, long-period (10–10,000 seconds or longer) measurements of these time-varying electromagnetic fields to determine subsurface resistivity from the mid-crust to depths of several hundred kilometers or deeper. At any given site, the measurements are obtained over days to weeks (or years, in some cases) to ensure a sufficient sampling of a region's deep geoelectric structure at long periods.

The USArray MT facility is operated by Oregon State University (OSU), funded by a subaward from IRIS. OSU operates the instrument depot for the EarthScope MT systems, handles data and data products, ships and stores instruments, builds and repairs hardware, and provides field computers and software support to field teams. Siting and construction of MT stations has typically been subawarded by OSU to specialized contractors.

History of Deployments. The USArray MT facility has completed more than 360 stations over six years. The configuration of the MT Transportable Array (MT-TA) was designed to closely mirror the spacing and footprint of the seismic TA. Collection of USArray MT-TA data began with the pilot deployment of 30 stations across the Pacific Northwest during the summer of 2006, and has continued with campaign-style field deployments each summer since then. Between 2006 and 2011, the MT-TA deployed across a quasi-uniform grid encompassing the northwestern United States (Figure MT-1). The deployment covered several features that were being actively studied with EarthScope's seismic TA, including the Juan de Fuca subduction zone, Cascade volcanic arc, High Lava Plains, Yellowstone hotspot track, and central and northern Basin and Range. In the latter part of 2011, the northwestern footprint was completed and the instruments were shifted to a target deployment across the Midcontinent Rift (MCR) in the US Midwest. The MCR footprint will be completed over the course of the 2012 and 2013 field seasons, and will extend from southern Missouri north to the Canadian border spanning most of Missouri, Illinois, Iowa, Minnesota, Wisconsin, and Michigan, and including sections of Indiana, Nebraska, and South Dakota, for a total of ~205 stations.

The deployment of seven permanent, MT backbone (MT-BB) observatories was completed by the summer of 2008 as part of the USArray construction phase. These backbone stations are deployed across the lower-48 United States to provide more continuous and deeper-penetrating, longer-period (up to 100,000 s) electromagnetic measurements than are typically available in temporary MT studies.

Data Collection and Products. The MT facility uses NIMS (Narod Intelligent Magnetotelluric System) instruments to record continuously the ambient electric field across orthogonal pairs of grounded electric dipoles, as well as the three orthogonal components of the ambient magnetic field. Typically, each MT-TA station-site records for two to three weeks after which the NIMS is relocated to the next MT-TA site. Data are stored on the field computer, then data and metadata are mirrored to the MT facility using cloud storage services accessed through the cellular data network. Raw data are archived into the IRIS DMC during the course of each field season and are publicly available immediately thereafter. Additionally, the facility calculates MT transfer functions, which comprise the primary data product for users of MT data. The transfer functions define the frequency-dependent linear relationship between components of the electromagnetic field variability measured at discrete stations. The transfer functions are available through the Searchable Product Depository (SPUD) system at the IRIS DMC. The MT-TA stations have maintained a data delivery rate of over 95% since the program started. MT-BB stations have seen more varied data return due to periodic outages related to the challenges of operating year-round, but have been near the 85% minimum threshold expected for permanent stations.

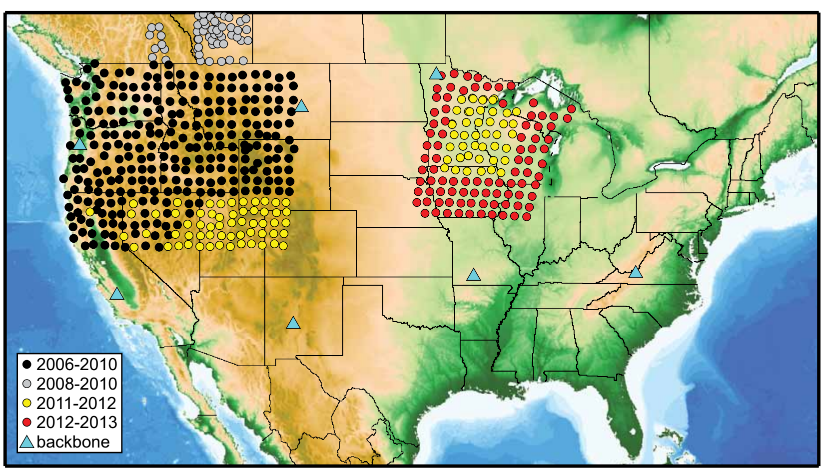


Figure MT-1. Deployments of USArray MT transportable array (circles) and backbone stations (triangles), through 2013. Stations in Canada (grey) were coordinated with USArray deployments by partners at the University of Alberta. All data, both USArray and Canadian, are archived at the IRIS DMC.

Scientific Justification

With data from the MT facility, the geoelectric structure of the crust and upper mantle beneath the western United States can be confidently resolved to a depth of several hundred kilometers (or deeper at MT-BB stations). Research groups from the United States and abroad are using recently developed 3D MT inversion codes to invert data from the MT facility, providing the first ever regional-scale 3D models for crust and upper mantle electrical structure (Patro, et al, 2008; Feucht and Bedrosian, 2012; Meqbel et al., 2012; Zhdanov et al., 2012). Figure MT-2 shows results from one such effort, based on inversion of the full complement of MT-TA sites from the northwestern United States. The MT data reveal extensive areas of high conductivity in the lower crust and uppermost mantle beneath the extensional Basin and Range, High Lava Plains, and Snake River Plain provinces, as well as beneath the Cascade volcanic arc. Key features in the 3D models include: stable Proterozoic lithosphere in the northeastern part of the domain, with the thickest sections coinciding with the Wyoming and Medicine Hat Cratons; oceanic lithosphere of the subducting Juan de Fuca Plate beneath the Coast Ranges; and the seismically fast "slab curtain" beneath eastern Idaho, which has been interpreted as stranded Farallon lithosphere. There are also some "holes" in the conducting layer, including beneath the Yellowstone hotspot where higher resistivities at 200–300 km depths may result from depletion of volatiles by previous (but episodic) melting events.

A particular focus of these early studies is the conductivity structure of the Yellowstone-Snake River Plain region (Zhdanov et al., 2011; Kelbert et al., 2012; Avdeeva et al., 2012). There, magnetotelluric measurements have defined a strong zone of conductive material mirroring the Yellowstone hotspot track (Figure MT-3). The zone of high conductivity appears confined to shallower than 100 km and it is probably indicative of the location of melt within the crust and upper mantle. Studies focused on the deeper structure of the Yellowstone plume also reveal a wide conductive zone dipping westward to over 300 km depth, coinciding with the general location of a zone of unusually slow upper mantle resolved in seismic tomography studies, and inferred to be the Yellowstone plume.

These exciting, emerging results were achieved despite the fact that many of the data were collected during a prominent solar minimum, which resulted in a diminished source for induced currents. This speaks to the quality of equipment, field procedures and data processing used by the EarthScope MT effort. As this solar activity now increases toward its periodic high in ~2014, the MT facility is well situated to capture new observations about the deep geoelectric structure of the North American continent. Preliminary review of data being returned from the MCR MT-TA stations indicates signals that may be associated with high conductivities in the rift region (this is an area of a well-known, and very significant geomagnetic anomaly).

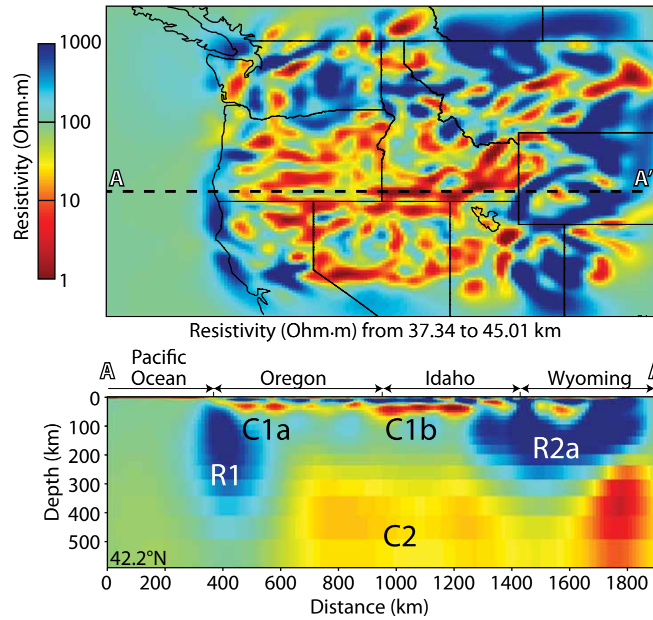


Figure MT-2. A 3D conductivity model of the northwestern United States based on inversion of 325 TA-MT sites (Meqbel et al., 2012). (top) Depth section, 37–45 km, showing spatial distribution of high conductivities (red areas C1 in cross section) near the Moho. (bottom) Representative east-west cross section at 42.2°N. R1 = resistive oceanic lithosphere; R2a = Wyoming craton; C1a, C1b = high conductivities (melt and fluids) near Moho; C2 = elevated asthenospheric mantle (consistent with moderate hydration).

Proposed Activities

3.1.7.1. MANAGEMENT AND GOVERNANCE

The MT facility will continue to be operated by OSU through a subaward from IRIS. Both IRIS and OSU will work proactively to ensure that the facility is well integrated into the larger framework of IRIS Instrumentation Services. The subaward PI/facility manager attends the meetings of the USArray Advisory Committee (USAAC) and reports to the IRIS Director of Instrumentation Services, who is charged with primary oversight of the MT facility. IRIS management will also conduct periodic subaward reviews of the MT facility to maintain a strong level of communication and ensure the facility meets all terms of the subaward.

The scientific direction of the MT facility is guided by the USAAC via its Electromagnetic Working Group (EMWoG). The EMWoG chairperson reports to USAAC and the membership comprises researchers from the academic community and the USGS. The EMWoG advises USAAC, the IRIS Director of Instrumentation Services, and the MT facility subaward PI on the science objectives of the MT facility and will be responsible for developing recommendations for rescoping activities should budgetary or facility-related changes arise. This management and advisory structure has led to a smooth construction and operation of the MT facility.

3.1.7.2. PERMANENT MT

The MT facility will continue to operate seven permanent backbone stations distributed across the lower-48 states. These long-period sensors provide high-quality, extremely long-period sampling of Earth's electromagnetic field. These stations will be periodically serviced to ensure continuous high-quality operation (as part of pan-Instrumentation Services collaboration, the backbone station in New Mexico is serviced by the seismic field engineers from the PASSCAL Instrument Center). The goal is to maintain 85% or higher data return at these sites, and a near-term focus will be hardening the sites against water infiltration and other factors that have resulted in downtime at several stations. Similarly, real-time telemetry will be improved through the implementation of a telemetry framework to buffer data at the stations, so that data records may be retrieved and error corrected on demand by instruction from the MT depot's telemetry server.

3.1.7.3. TRANSPORTABLE MT

The MT-TA will systematically operate in discrete regions across the currently unoccupied portions of the lower-48 states following completion of the established MCR footprint in 2013. Sites will be occupied at a target rate of 70-75 sites per year in the lower 48 states, using field teams subcontracted to OSU. Operations in the southern half of the United States, where seasonal obstacles are reduced, should allow an early start and later finish to each field season.

The facility will operate and maintain 21 NIMS receivers dedicated for deployment as MT-TA stations. The MT-TA will continue to use, on an as-available basis, instruments from a general purpose MT instrument pool of 25 NIMS, also operated at OSU as part of the National Geoelectromagnetic Facility (NGF). Fielding these additional instruments increases the efficiency of field operations. Plans also call for the replacement/addition of one MT instrument per year. Maintaining a high standard of data return remains an operational priority.

The USAAC and EMWoG will continue to guide decisions on "footprint" selection, factoring in the results of the NSF-sponsored MT siting workshop held in 2008. The USAAC and EMWoG hold as a strong goal the completion of a continuous lower-48 MT grid by the conclusion of EarthScope. Completing this "full 48 states" coverage will require either supplementary funding or increasing the current interstation spacing, and options will be discussed by the EMWoG, USAAC, and IRIS Board of Directors. As the USArray seismic TA deploys into Alaska, the seismic and MT operations will explore a limited piggyback deployment of MT instruments, with station spacing of 200–250 km (using just the hub locations of the seismic TA's planned hub and spoke deployment plan). The USAAC and EMWoG have endorsed this concept for limited use of MT instruments in Alaska, but such plans are contingent on the final form of the seismic TA operations, the suitability of the hub sites for MT observations, and other factors.

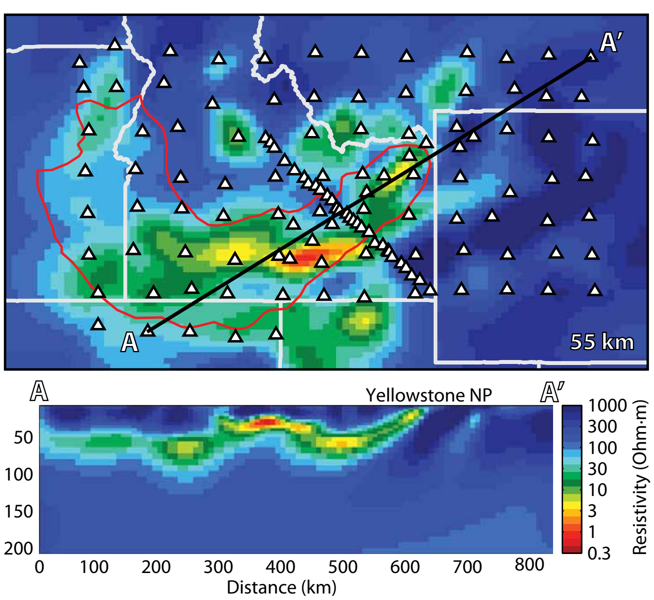


Figure MT-3. Inversion of MT-TA data in the region of the Yellowstone hotspot track (Kelbert et al., 2012). (top) Map view of resistivity at 55 km depth. (bottom) Profile A–A′, parallel to the Yellowstone hotspot track along the Snake River Plain and Yellowstone showing a conductive anomaly at or below the crust-mantle boundary throughout the region. This conductive feature intersects the surface near the modern Yellowstone caldera.

3.1.7.4. FLEXIBLE MT

PI-driven deployments will be able to use MT-FA instruments, as well as NIMS and ultra-wideband Zonge Zen/5 electromagnetic/MT instruments from the NGF instrument pool. The MT facility will maintain close contact with NSF and PIs to ensure prioritized and complete availability of instruments for deployment. Training will be provided to PIs and their teams prior to going into the field, and they will receive support for processing their data after returning from the field.

3.1.7.5. DATA

The facility will continue timely archiving of MT data following MT-TA field campaigns and visits to MT-BB stations. Additionally, transfer functions for each station will continue to be delivered to the IRIS DMC. The MT group will work closely with the IRIS Data Services group to properly represent MT data in SEED format, and to make the transfer functions readily available via the SPUD system. Evaluation and development of more refined MT data quality metrics will continue, with the goal of quantifying performance, with reasonable confidence limits, for periods of 20 to 10,000 seconds.

3.1.8. IS-COORDINATED ACTIVITIES

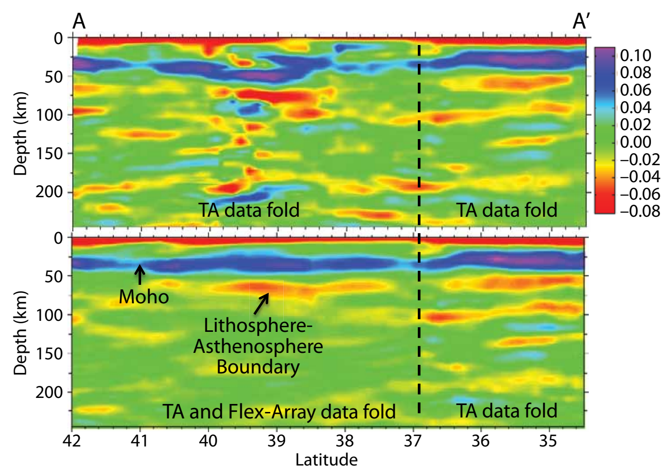
The forefront of seismological research is constantly evolving. New scientific questions drive new algorithms and techniques, which in turn stimulate the need for new observatory and equipment capabilities. The resultant new data sets lead to even newer techniques that better exploit the data and can lead to new geological hypotheses. This feedback loop has been present since the inception of IRIS as a community facility to implement and operate the seismological infrastructure that supports the ever-changing science requirements of the community. The revolution in instrumentation and data standards that emerged in the 1980s was championed and adopted in the early years of IRIS—24-bit data loggers, broadband feedback seismometers, real-time telemetry and advanced data management systems—and have served to put the US academic community at the forefront of global seismological research. While there has continued to be evolution in IRIS utilization of these technologies over the past 20 years, revolutionary technologies that are now available or on the close horizon offer the opportunity to stimulate another significant advance in seismological research. To this end, IRIS IS will undertake and coordinate four key instrumentation activities described below that will address the communities' future instrumentation needs; build the foundations of future observatories; and promulgate knowledge and best practices to enhance data quality, availability, and impact.

- Leverage new technological opportunities to define and demonstrate a forward-looking New Technology (NT) portable instrument pool to address the community's needs for infrastructure that supports the needs of the evolving science.
- Seed the exploration of a Global Array of Broadband Arrays (GABBA)—a worldwide distribution of arrays—for addressing a number of key science objectives, primarily in deep Earth structure and source dynamics of large earthquakes.
- Lay the groundwork for a possible Subduction Zone Observatory (SZO) spanning the margin of the eastern Pacific Ocean, over 18,000 km from the Aleutians to the tip of Tierra del Fuego.
- Share IRIS' instrumentation experience to improve international seismological networks for the benefit of both research and hazard applications.

3.1.8.1. PAN-IRIS NEW TECHNOLOGY

Instrumentation Services will implement leading-edge technology to support PIs whose science objectives exceed the capabilities of today's equipment. Virtually every field experiment, regardless of scale, seeks to use more sensors to improve resolution so as to avoid spatial aliasing, edge effects, and other characteristics of undersampling (Figure COORD-1). However, existing systems do not scale well to very large numbers of sensors. The logistics introduced by the size, weight, and power consumption of current systems limits the size of experiments, and the cost and complexity of the instruments have further limited the number of units that can be acquired and maintained.

The NT effort will create a prototype system to address the community's expressed desire for portable seismic sensing systems that can support large numbers of sensors ("large N") that can be deployed easily and quickly. Such systems open the door for PIs to realistically consider designing experiments requiring potentially hundreds to thousands of sensors in a single experiment (Figure COORD-2). A wide range of existing deployments are already hitting the limits of the current instrument pool, including traditional PASSCAL and Flexible Array experiments, polar deployments, and aftershock studies. Other experiments, such as passive-source high-resolution arrays, cannot even be implemented without a dramatic increase in the number of sensors and an equally significant decrease in the deployment-related field logistics. This need is particularly acute for relatively unstudied but operationally challenging environments such as volcanoes and glaciers, where the availability of large N systems has the potential to yield transformative scientific results.



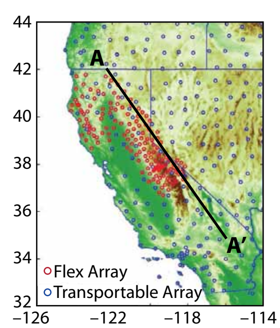


Figure COORD-1. (above) Receiver function image along the Sierra Nevada range. (top) Transportable Array (TA) data-only image. (bottom) TA data augmented with Flexible Array (FA) data. The TA-only image contains significant imaging artifacts and is unreliable. Yet, the combined TA and FA image is much higher quality, illuminating the negative velocity gradient associated with the lithosphere-asthenosphere boundary. The combined data image fold is enhanced five times. The filter band is 30–2 s and the image bin size is 100 km. (left) Topography, cross section, and station locations. The circles show the FA stations (red) and the TA stations (blue). *(Figure courtesy of Ken Dueker and Katie Foster)*

The key technical issues for creating next-generation portable systems are common across multiple IRIS programs. Thus, the NT effort will lead to increased observing capabilities and operational efficiency across IRIS. A side benefit of an equipment pool that contains a much larger numbers of sensors is increased instrument availability for small experiments, which may alleviate some pressure on the traditional broadband pool. Finally, the new technology effort will directly inform, if not directly address, other portable sensor pool recapitalization plans (e.g., the single-channel Texans or three-channel broadband instruments) by providing comprehensive user-needs analysis and validated technical performance characteristics. IRIS has been deferring its investments in refreshing the portable instrument pool while awaiting the maturation of developing new technologies that are now available and this project will guide these investments going forward.

While the technology applicable to seismic instrumentation is changing rapidly, there are no silver bullets as the fundamental laws of physics still apply (i.e., the physics dictates certain relations between weight, power, bandwidth, and telemetry). System configuration and performance trade-offs must be made. To this end, user needs must be defined, system specifications and requirements set, and performance and interoperability validated. This systematic approach is key to realizing this first demonstration of a system that can be scaled to very large numbers of highly-portable sensors and relies on historical experience with current instrumentation. This IS-coordinated activity will define both the portable instrument pool of the future and will substantially expand the scientific opportunities for the design and implementation of all kinds of seismic experiments. There will also be an impact far beyond IRIS, as groups around the world follow IRIS' lead in technology selection, implementation, and operational practice—resulting in a multiplier effect for the scientific community based on IRIS' instrumentation investments.

Scientific Justification. A wide range of science objectives require deploying sensors in large numbers, whether in tight spatial arrays or distributed over larger areas. In May 2012, 27 researchers and instrumentalists representing a wide spectrum of seismology interests came together in Seattle for a full-day meeting to explore the science needs and goals for large N experiments. More recently, at the IRIS Workshop in June 2012, over 100 people participated in a standing-room-only special interest group discussion on "Next-Generation Instrumentation for Portable Seismology." Table COORD-1 is based on the discussions at these meetings and captures the key science objectives enabled by large N sensor systems.

Proposed Activities. This effort will use well-defined systems engineering processes to specify, acquire, integrate and deploy a sensor system based primarily on existing and emerging technologies (commercial off the shelf [COTS] or COTS-ready technology). The project will not, to any significant degree, be engaged in component design and development. The first year of the multiyear process will focus on conducting community-driven assessments designed to further identify user needs and match them to system performance specifications (e.g., bandwidth, dynamic range) and operational characteristics (e.g., size, weight, power). In subsequent years, the resultant system specifications will drive validation testing of the underlying technology, followed by acquisition, system integration, and testing culminating in the deployment of a demonstration system. The system will be designed to address the community identified engineering, logistical, and environmental challenges, and provide a means to develop and test practical field operations and instrument management protocols as well as evaluate data quality.

The number of sensors in the demonstration system will depend on the final cost per unit with the goal to create a system consisting of at least several hundred sensors in order to achieve the necessary scale for meaningful evaluation. In the fourth and fifth years of the award, the system will be tested in PI-led field experiments. Thus, even this demonstration system will enable new science. Critical lessons learned from the prototype

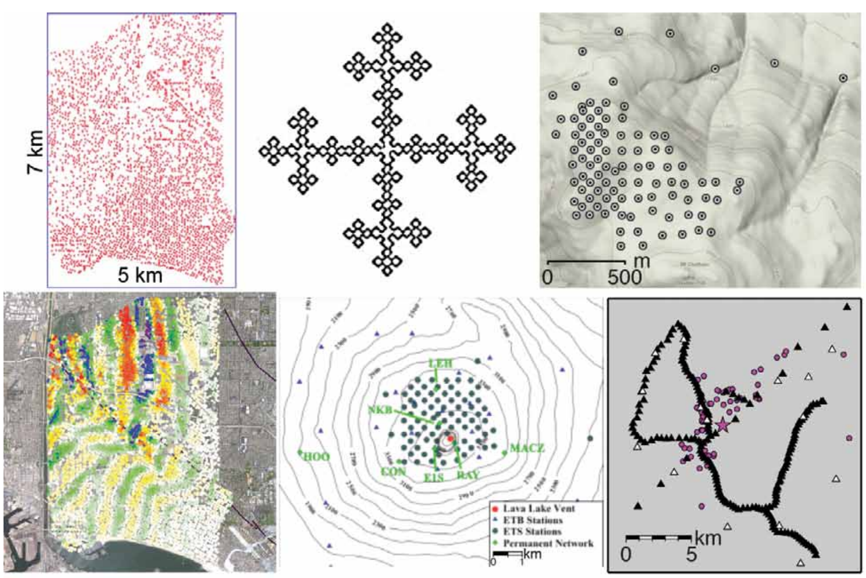


Figure COORD-2. Examples of large N instrument deployments and applications, assembled from the large N workshop, Seattle, WA, 5/24/2012. Top row, left to right: NodalSeismic Inc.'s deployment of 5,000 sensors across 35 km^2 in Long Beach, CA; fractal array (antenna) design concept (courtesy of Jesse Lawrence); array deployment to study episodic tremor and slip (courtesy of Ken Creager). Bottom row, left to right: Wavefield propagation imaged by the NodalSeismic Inc. deployment; a sample volcano array study on Mt. Erebus; traditional (white stations) and densified (black stations) rapid array deployments following the 2011 Virginia earthquake and its aftershocks (magenta symbols).

Table COORD-1. Summary of science targets and goals and associated sensor deployment strategies enabled by large N systems. These themes emerged over the course of the numerous presentations and extensive discussion at the Seattle and IRIS workshop meetings.

Target Subject	Science Goals	Required Sensor Deployments
Earthquake physics	• Distribution and timing of seismicity clusters • Deep fault structure • Evolution of faults with time • Interconnections of slip, tremor and earthquakes	• Proximal recordings over large regions of aftershocks • Long-term networks to capture fault rupture for significant earthquakes • Low noise, dense networks for small amplitude tremor signals
Structure/ imaging	• Earth structure without spatial aliasing and spurious imaging artifacts • Crustal structure and properties, such as anisotropy • Lithosphere structure and lithosphere-asthenosphere transition • Mantle and core structure - bridging gap between imaging scatterers and full volumetric heterogeneity • Determine empirical structure through slowness, amplitude and spatial evolution of wavefield	• Dense deployments across key crustal targets • High resolution 2D regional scale deployments • Array deployments optimized for continental and global scale observations • Array deployments optimized for continuum seismic recording and wavefield gradiometry
Volcanoes	• Temporal changes in magmatic systems • Seismic interferometry of highly scattering volcanic systems	• Deployments in harsh, remote volcanic environments
Energy and the environment	• Improved facies characterization • Imaging geology beneath high-velocity surface layers • Porosity / permeability estimates • Mapping thin layers with P and S attributes	• Deployments with extreme sensor densities normally only available via cabled systems • Operations in urban and rural settings
Polar, fluvial and cryosphere	• Sub-ice sheet Earth structure • Climate change • Sub-glacial waterflow and erosion • Ice thickness • Impact of sea level rise on calving glacier systems • Coupling of rivers and the solid earth	• Rapid deployment of instruments in environments with high field operations costs • Deployment on and around glaciers • Low impact deployments in sensitive environments • Extremely dense networks to capture scattered wavefield
Hazards	• Operational aftershock forecasting • 4D mapping of post-earthquake stress and strain fields • Detection, mapping, forecasting of eruptive activity • Pre-, during-, and post-earthquake analysis of the behavior of the built environment	• Rapid deployment of dense sensor arrays over aftershock zone - to enable use of exploration industry imaging techniques • Deployment around volcanoes showing pre-eruptive activity • Deployments in or near structures

array will be applied in future years to creating a sustainable portable large N system that supports PIs in acquiring unique and novel seismic data. The net result will be an enhanced capability to operate and maintain the portable instrument facility going forward in a cost-effective manner.

3.1.8.2. GLOBAL ARRAY OF BROADBAND ARRAYS

The proposed Global Array of Broadband Arrays will provide a detailed view into Earth via a global distribution of wide-aperture broadband arrays (Figure COORD-3). Clearly, the development of such a facility is a long-term international effort, but momentum for building such a facility is increasing. There were well-attended special interest group discussions on the topic at the fall 2011 meeting of the American Geophysical Union, followed by a subsequent community-driven meeting at the 2012 IRIS Workshop. A workshop on the same topic is planned for early 2013 and already a number of key international participants have indicated their interest in attending. The foundation of this ambitious effort will be a prototype GABBA array site within the conterminous United States, which can be created through the careful leveraging of NSF's investment in TA stations. This first of (hopefully) many GABBA sites will demonstrate the GABBA concept and provide a testbed for array capability and operational models. Locating the array in the eastern United States will provide scientific synergies with GeoPRISMS' Eastern North America primary site. The international community will be engaged to encourage follow-on GABBA arrays.

Scientific Justification. *The Seismological Grand Challenges* report (Lay, 2009) recognizes that seismic arrays offer great potential for resolving important questions regarding such

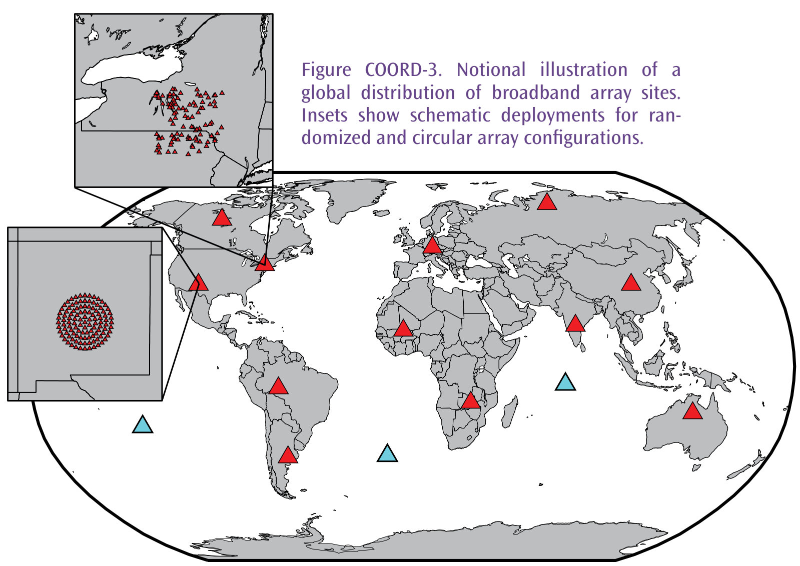


Figure COORD-3. Notional illustration of a global distribution of broadband array sites. Insets show schematic deployments for randomized and circular array configurations.

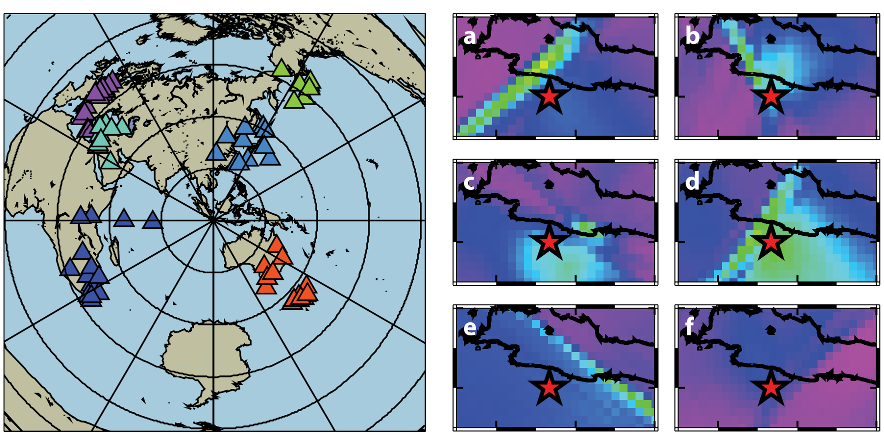
diverse topics as the nature of the lithosphere-asthenosphere boundary, how temperature and compositional variations control mantle and core convection, and how Earth's internal boundaries are affected by dynamics. More recently, the report *New Research Opportunities in the Earth Sciences* (NRC, 2012) states (emphasis added):

EAR should pursue the development of facilities and capabilities that will improve spatial resolution of deep structures in the mantle and core, such as ***dense seismic arrays that can be deployed in various favorable locations around Earth****… This will provide definitive tests of many hypotheses for deep Earth structure and evolution advanced over the past decade. The large scope of such facilities will require a lengthy development and review process, and building the framework for such an initiative needs to commence soon.*

GABBA sites, working in concert and individually, will provide valuable information on deep-Earth structure as well as providing important constraints on rupture processes associated with large earthquakes. Figure COORD-4 illustrates the imaging power realized through combining multiple arrays. In this example, the simultaneous use of multiple regional networks/arrays yields an image far superior to what a single array can achieve. Arrays will also image rupture in ways that may transform our views of earthquake processes. For example, EarthScope Flexible Array instruments, deployed in Texas and New Mexico, were used to image a reversal in rupture propagation during the 2010 El Mayor-Cucapah earthquake. Such features of earthquake ruptures are difficult, if not impossible, to image without the power of arrays and in some cases are unanticipated prior to their observation—resulting in fundamental changes in our understanding of earthquakes source physics.

Proposed Activities. The core of the prototype GABBA will be an existing 3 x 3 portion of the TA grid (nine stations, ~20,000 km²). This subset of TA stations will be selected based on a combination of favorable terrain and permitting, with an emphasis on avoiding cultural noise so as to maximize data quality. If possible, the selected grid will include TA stations that are planned for external O&M support (see CEUSN discussion under WBS 3.1.6), to reduce long-term operational costs. Nine additional stations will be subsequently installed within the grid, for a total of eighteen stations. The array design for the infill stations will be developed based on community modeling, as well as the analysis of data from (smaller) existing arrays. The infill sites will repurpose TA station hardware not required for the Alaska deployment. Station components that the TA requires for redeployment to Alaska, as well as consumable items (e.g., batteries, plastic station tank), will be replaced.

Construction of the infill stations will be most efficiently accomplished in early FY14, when experienced TA construction and installation crews will be available for temporary retasking. Station maintenance and data flow will be managed in tandem with the remaining operating TA footprint. The GABBA project will take over the O&M of all 18 array elements once regular TA operations conclude in the lower-48, at the end of FY15. Stations will be operated at increased sample rates, relative to regular TA stations to encourage synergistic use of the data for local earthquake studies and related activities (the GABBA design does not require high sample rates). This project will naturally encourage a temporary or long-term infill with more traditional short-period or intermediate-period array elements, ideally using a temporary deployment of the large N system. Demobilization is not included in this plan as it is outside the 2014–2018 time window.



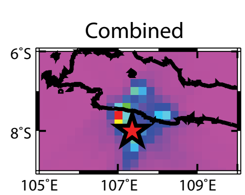


Figure COORD-4. Data from regional networks / arrays (map on left) were used to generate semblance source maps (top six figures on right) for the onset of the M7.4 Java earthquake on September 2, 2009. These source maps are then combined to produce a dramatically improved semblance source map (bottom right). *(Roessler et al., 2010)*

3.1.8.3. SUBDUCTION ZONE OBSERVATORY

In the years after the completion of EarthScope, it will be possible to jointly leverage the highly successful EarthScope USArray and PBO efforts to create an unprecedented 18,000 km long Subduction Zone Observatory along the length of the east Pacific margin. An SZO stretching from the Aleutians in the north, to the tip of Tierra del Fuego in the south, can enable research on all facets of subduction zone processes (see highlight box in EarthScope section of this proposal). This effort provides the opportunity to integrate ocean-bottom and land-based seismology and geodesy and blend the efforts and experience of the broader IRIS and UNAVCO facilities to launch a major international effort.

The seed funding proposed here will be used to develop and leverage, in collaboration with UNAVCO/PBO, additional partnerships to stimulate broad national and international participation in an organizational workshop. Creating an SZO is clearly a long-term project that will require substantial interactions with the international scientific community in the coming five years in order to motivate future investments necessary for implementation.

Scientific Justification. An SZO will provide an integrated view of an entire continent-ocean plate boundary system. The observatory will encompass multiple subduction geometries, the transition into transform motion, multiple smaller tectonic plate geometries, the contrast between regions of vastly different seismicity rates, volcanism, great earthquakes, and areas with known tsunami-genic potential. Instrumentation sufficient to observe episodic tremor and slip has only been fielded along a small part of the SZO. The societal relevance of basic research within the SZO is extremely high, given the population density all along the west coast of the Americas.

Proposed Activities. An organizational workshop will bring together a cross section of international interests across multiple disciplines, including at least seismology, geodesy, geology, geochemistry, geodynamics, volcanology, and atmospheric sciences. Principal instrumentation interests include land- and ocean-based seismology, geodesy, side-aperture radar, LiDAR, strain, and infrasound. The workshop will provide a means to inventory the existing national and international assets, motivate and possibly coordinate planned investments, and help identify the required investment in offshore technologies.

The IRIS Instrumentation Services, International Development Seismology, and Data Services will work with UNAVCO to build on existing relationships in the region to encourage broad geographic representation in the workshop. A key workshop goal will be representation from all international stakeholders (particularly the 13 countries bordering the East Pacific) and to encourage open data flow and sharing of best practices across the region. The workshop will dovetail with the first of the best practices training courses (described below), which will be focused on enhancing the seismological infrastructure in Central America and South America.

3.1.8.4. TRAINING AND BEST PRACTICES

IRIS Instrumentation Services continuously seeks to maximize data quality and availability as well as increase the efficiency of IRIS' instrumentation facilities. By sharing knowledge gained and lessons learned from over 25 years of operating seismological infrastructure, IRIS can provide others with a set of best practices and in the process further the broader community's science. To this end, a series of best practices training courses will encourage the creation and/or operation of high quality, sustainable networks. Two types of courses are planned, targeting two different audiences: network managers and network installers/operators. The network manager course will focus on guidance for best practices in designing, acquiring, implementing, and sustaining seismic networks, and will be targeted at managers at the agency/government level. IRIS will collaborate with peers at organizations and agencies within the United States to facilitate the course. The network installers/operators courses will provide training in best practices for siting, installing, and operating seismic networks. Topics to be covered include vault construction, station installation, station subsystems (sensor, power, communications, data acquisition), and data and metadata management. These will be "hands on" courses that involve a mix of classroom and field activities to facilitate in-depth information exchange. "Networking" among the participants will be a strongly encouraged by-product of the courses, as regional peer-support structures can greatly enhance successful network operations.

Scientific Justification. The scientific return for these training courses will be many times the investment. The courses increase the likelihood that more instruments will be successfully installed and that observatories and networks will produce better data that is openly shared. The net result will be increased global and regional station coverage.

Proposed Activities. A total of four courses, targeted for two geographic regions, will be held. A "manager" and an "installer/operator" course is proposed for each region. Attendance at each pair of courses will be coordinated to reach multiple levels/specialties within the participating organizations. The first course pair will focus on Central and South America, as IRIS can build on numerous existing relationships in this region (both organizational relationships and peer-to-peer relationships established though numerous PASSCAL experiments and other exchanges) and will provide synergy with the more science-focused SZO workshop. The second target area will be Southeast Asia, as a natural follow-on to the recent Metadata Workshops and Advanced Studies Institutes held in that region by IRIS Data Services and International Development Seismology. IS, IDS, and DS groups at IRIS will work closely together to build on existing relationships, identify key participants and their roles within their own organizations, and to maximize the potential for follow-through by workshop participants.

3.2. DATA SERVICES

Overview

Data resources are only as good as a researcher's ability to explore them. The facilitation of data discovery, preservation, and dissemination are therefore essential services of the IRIS facility. These goals are particularly challenging because of diversity and the large and growing number of end users of seismic data. In addition to its traditional uses in earthquake mechanics, volcanology, explosion detection, and Earth structure studies, seismic data have recently been applied to glaciology, geomorphology, oceanography, and atmospheric physics. These novel and emerging applications place an even larger onus on the facility to provide high-quality, standardized data along with the necessary tools for efficient data exploration and utilization.

Data Services (DS) provides for (1) secure and standardized archiving and preservation of unique, irreplaceable, and continuously accruing data and metadata assets; (2) generation and distribution of data products; (3) data access to researchers, educators, students, government agencies, the public, and other users, and (4) continuous and versatile quality assessment and other data review. DS interacts strongly with IRIS Instrumentation Services data collection activities (Portable Seismology, EarthScope, and GSN), and with associated EPO, and International Development Seismology efforts described in this proposal. IRIS DS provides key technical and methodological underpinnings driving US collaboration and leadership in global free and open data access. Overall, DS operations ensure the efficient and multilateral flow and use of data for the world's largest archive of quality-controlled, fully metadata-associated, and professionally managed seismic data to advance US and international scientific and broader communities in the public interest.

Data Services meets this challenge of serving a diverse community by establishing and maintaining a uniform and highly efficient global database of digital data recorded by research seismographs deployed over the past five decades (and, for some historical data sets, stretching back to early twentieth century). This archive is coupled with a customizable and robust data discovery and interpretation toolset to facilitate its broad applications. Data Services receives and conserves data and metadata from principal investigator-driven science and educational experiments conducted by a broad user community in a fully described and systematized database structure. This structure enables the efficient use, integration, and reuse of internationally standardized data collected from a large number of partner organizations and peer-reviewed seismological projects, including those funded by NSF, DOE, USGS, and other US and international programs. DS data request tools flexibly facilitate analyses and re-analyses of data from individual projects, and also allow the integration of multiple experiment/network DS resources into user-specified data volumes that optimally span original data source, time, and/or geographic divisions. Such customized data retrievals may be carried out either by accessing predefined IRIS DMC virtual networks of established community interest, or via a unique set of user-determined criteria. This data request versatility permits efficient application of new or expanded analysis techniques to address both established and novel and evolving scientific goals using data resources that may have been originally collected for entirely different objectives.

Synergies Between UNAVCO and IRIS Data Centers

Both IRIS and UNAVCO operate full service data centers to manage geodetic and seismological time series, and a wide array of geodetic and seismic imaging products. As we enter into the next five-year cooperative agreements between our organizations and NSF, we will continue to work together toward service integration between our data centers. IRIS and UNAVCO are involved in two significant projects where synergies between our data centers will continue to be enhanced.

- With funding from the European Commission and from NSF, the COOPEUS project is an effort to coordinate data activities in five project pairs between Europe and the United States. Of specific interest are the coordination of data management between the European Plate Observing System (EPOS) and EarthScope. UNAVCO's focus will be on vertical integration of web service techniques within geodetic data centers in the US and Europe while IRIS will work with US and European Data centers toward vertical integration of web services within seismology.
- NSF's EarthCube is a coordinated GEO- and OCI-sponsored initiative to create a data and knowledge management system in support of highly data-driven research across the geosciences in the 21st century. IRIS and UNAVCO are partners in the Service Based Integration Platform for EarthCube (SBIP-E). UNAVCO and IRIS are actively working on horizontal integration between geodetic and seismic data, as well as data sets from other geoscience domains, as part of EarthCube.

In addition to COOPEUS and EarthCube, IRIS and UNAVCO data centers are collaborating to make high rate displacement time series derived from geodetic observations available to the seismological community. Over the course of this five-year proposal the UNAVCO Data Center will provide the IRIS DMC with displacement-grams for distribution to the seismological community in formats and via services supported at the IRIS DMC.

Developed jointly by UNAVCO and IRIS.

Proposed Activities

3.2.1. MANAGEMENT

Data Services appears in the management structure at a parallel level with Instrument Services, and Education and Public Outreach. DS includes the Data Management Services (DMS) program. The DMS components include the IRIS DMC in Seattle, associated activities at the University of Washington, the IRIS/IDA Data Collection Center and tight links to the EarthScope Array Network Facility, both at the University of California, San Diego, the USGS Albuquerque Seismological Laboratory, the PASSCAL Instrument Center at New Mexico Tech, and the Kazakh National Data Center.

The DMC serves as the principal distribution point and staffing center for supporting data activities, and includes three strongly interacting groups: the Data Management (operations) Group, the Information Technology Group, and the Projects Group (which currently focuses on developing products and services). The DMC maintains and advances essential input, output, quality control, and other services and capabilities that are broadly used by the IRIS and international research communities. The heads of the three sections, along with the Director of Data Services and the DMC Office Manager, are organized into the Management Team. Working with the Data Management System Standing Committee (DMSSC) and other elements of IRIS community governance, the DMC Management Team ensures that projects and developments remain adaptively aligned with community needs and make optimal use of IRIS and community resources.

3.2.2. GOVERNANCE

The DMSSC governs the Data Management System. DMSSC members are drawn from the research community, including university researchers and government agencies, and are appointed by the IRIS Board of Directors. Normally there are nine members of the DMSSC each serving for a three-year term. The DMSSC has one working group that reports to it. The Data Products Working Group provides guidance to DS related to the types of products that should be produced by DMC staff or community based products that should receive support from Data Services.

3.2.3. DS AND DMC OPERATIONS

Acquiring, Archiving, and Preservation. DMS core activities of archiving and preserving data are essential for the sustained support of research, and thus they remain the highest-priority activity for the foreseeable future. The primary responsibility of the DMS is to act as the conduit through which the US and global seismological community accesses high-quality data delivered by almost 20,000 seismic stations spanning five decades. Data volumes are accruing at a high but manageable rate, with the current archive of 170 terabytes (as of April 2012) increasing in size at approximately 30 terabytes per year. We estimate that this increase is manageable for the foreseeable future with existing DMC support from a connectivity, technological, and staffing perspective. The rate at which data are being delivered from the DMC to the global scientific community is increasing exponentially, attesting to the keystone position that IRIS holds in seismological research and to the generally increasing demand for diverse data volumes. While the growth in delivered data is a positive testament to the value of the DMC, managing its rate of increase is more of a concern than accommodating the more slowly increasing ingestion rate. Meeting the increasing demands of data distribution will require the DMC to continue to explore and implement new distribution mechanisms and efficiencies in data management (Figure DS-1).

3.2.4. INFORMATION TECHNOLOGY

The IRIS Knowledge Base. As IRIS continues to serve an ever-growing and diversifying community, the number of user questions directed to a relatively small DMC staff continues to grow. To continue to serve an expanding community without devoting more resources, the DMC will continue to promote the IRIS Knowledge Base, a self-help interactive system that answers frequently asked questions.

To augment the Knowledge Base, we will implement a self-help mail list server where users can direct questions to the broader IRIS community. This system will emulate the very popular SAC-HELP list server used by the SAC (seismic analysis code) community.

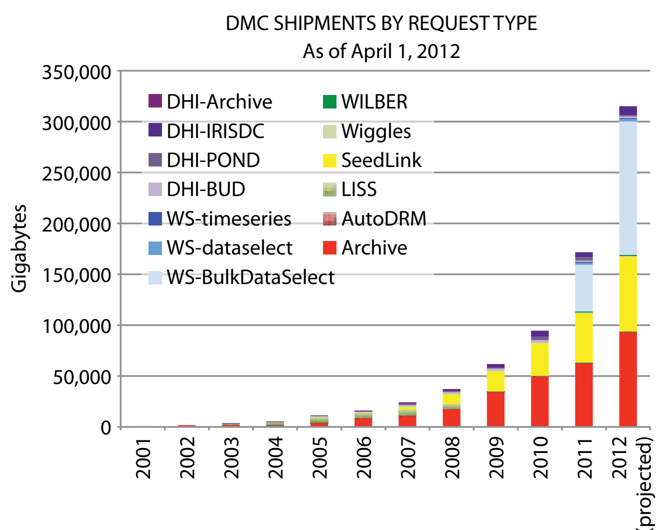


Figure DS-1. Data, measured in gigabytes, distributed annually by the DMC since 2001. The red portion shows traditional (typically email-based) requests, the yellow represents real-time data distributed by using the SeedLink protocol, the variant blue shades show the data sent via web service-based mechanisms introduced in December 2010, and the purple shades show data sent via the Data Handling Interface (DHI) mechanism. We project delivering more than one-third of a petabyte to the research community in 2012. Web services, first introduced in 2010, have grown very rapidly in popularity, and are anticipated to dominate overall data distribution methods beginning in 2012.

Web Optimization. The IRIS DMC has a rich web presence, but the associated thousands of pages need constant maintenance and organization. As user demands increase, it is essential for users with varying capabilities, interests, and experience levels to be able to quickly navigate the IRIS web pages for information, and that this information be returned to users in a format they can most readily use. We will devote much effort to improving the usability of the IRIS web site and the overall user experience. The improvements will be across all of IRIS, although the initial focus will be directed toward DS.

3.2.5. PRODUCTS AND SERVICES

New Data Distribution Paradigm: Web Services. The IRIS DMC has developed powerful and practical web-based mechanisms through which the scientific community can access waveform data and associated metadata, earthquake catalogs, data products, and a variety of other types of information. These methods are termed web services, and as we use web services in this proposal we mean the ability for a researcher to extract information from the DMC using simple URLs and well-documented query parameters. The availability of these web services means that researchers have simple access to most information that they need from the DMC. This access can be through a browser or through client applications or scripts running on the researcher's local computing system.

Meeting the needs of the broader scientific community and increasing data handling efficiency is a focus of future developments in web services. The DMC will continue to develop and distribute a variety of scripts, libraries, and methods that allow researchers to use these web services. The DMC will also revamp existing request tools to leverage this web services development and create new techniques to streamline data into widely used processing platforms such as MATLAB. Considering the growing scope of interdisciplinary Earth science research and that many stations now produce data from a wide variety of nonseismological instrumentation (e.g., barometers, infrasound, hydrophones), it is timely for IRIS to support processing capabilities for making these nontraditional data very easily accessible (i.e., instrument corrected, resampled, output in simple formats) to a broader community of researchers in seismology and other disciplines.

IRIS coordinates its activities in web service developments with FDSN partners, and will work with FDSN data centers to offer federated data access through these methods. We are presently focusing this effort on core web services by working with European data centers in the Netherlands, France, Germany, Italy, and Switzerland, and with US data centers at Caltech and UC Berkeley. These services provide access to a waveform data, station metadata, and earthquake catalogs in a uniform manner. They feature standard methods of formulating search and query parameters, and ensure that the results of a query are returned to the user in a uniform way from any of the federated data centers.

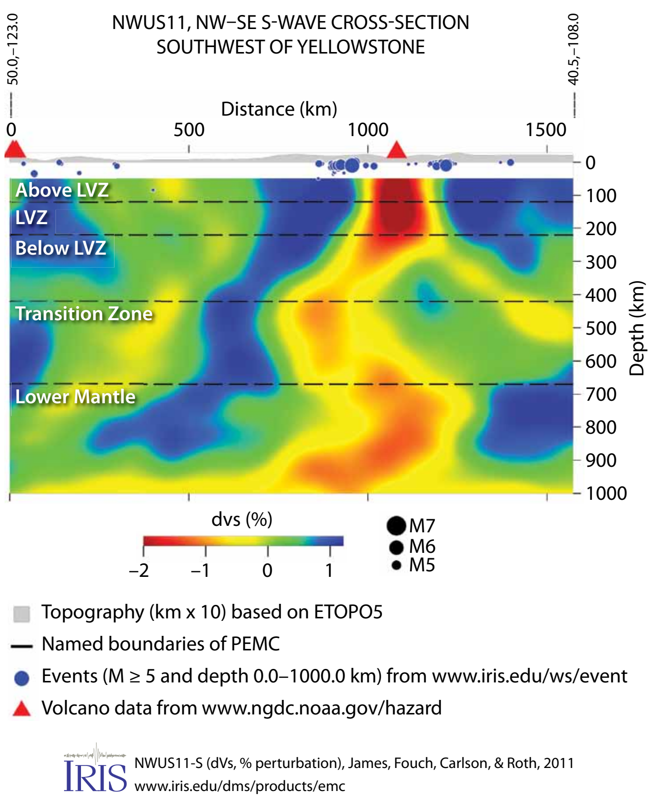


Figure DS-2. A NW-SE cross section southwest of Yellowstone of model NWUS11-S (James et al., 2011) created using the IRIS Earth Model Collaboration's Generalized X-section Viewer. The cross section also shows earthquakes (blue dots) and volcanoes (red triangles) in the vicinity of the profile (within ±0.5°) with earthquake symbols scaled based on their magnitude. The section colors indicate variations in shear velocity perturbations and show a low-velocity feature that extends to the Snake River Plain/Yellowstone hotspot.

Enhanced Processing Capability: Cycles Close to Data. For data centers with hundreds of terabytes of data, such as the IRIS DMC, it is difficult to transfer large fractions of the archive to end users, and it may be difficult for them to ingest and use such volumes with local resources. For this reason, the DMC will examine models whereby a copy of the DMC's holdings can be stored at a high-performance computing center or another highly capable facility that supports enhanced processing and storage capacities. The DMC would then enable users to upload their processing algorithms and access very large components of the data archive at that center via efficient web service access to locally served data.

For example, the University of Washington currently calculates envelope functions of all the data in the DMC to detect fault zone or other tremor activity around the globe. This study requires access to a large fraction of the entire DMC archive and invokes considerable processing. To enable this activity, the University of Washington seismology group uses the Hyak computational facility operated by the e-Sciences Institute at the University of Washington. This is one model of how IRIS can provide processing capability to make very large data

IRIS Web Services Examples

DATA ACCESS SERVICES

- Waveform access
- Waveform availability
- Complete station metadata
- Time-series responses in multiple formats
- Earthquake catalogs
- Virtual network
- Product access

PROCESSING SERVICES

- Units conversion/Gain correction
- Instrument response deconvolution
- Filtering (bandpass, low pass, high pass)

OTHER SERVICES

- Format conversions
- Distance/azimuth calculations
- Flynn-Engdahl geographic regions

analysis studies tractable for the user community. Funding for this type of activity can be acquired from external sources, thus, not requiring significant funding from core IRIS.

Product Generation and Management. Data can be most useful when they are fully integrated into research-ready products. To facilitate both research and EPO efforts, IRIS develops and manages a suite of community-vetted products derived from observational data. These products include Teachable Moment activities following significant earthquakes, global earthquake moment tensor estimates, digitally registered seismically derived Earth structure models, and ground motion visualizations and record sections. Some of these products, such as the global moment tensor database, are among the most widely used of all seismological results that feed directly into research. IRIS staff develop and generate in-house products, and the broad research community generates externally developed products that are hosted at the DMC, for long-term curation, exploration, and distribution. IRIS will also continue to develop and maintain the associated SPUD management system for data products. Table DS-1 summarizes recent product activities.

CROSS WBS ELEMENT TASKS [WBS 3.2.3, 3.2.4, 3.2.5]

Some tasks Data Services propose to undertake require resources from multiple WBS elements, including efforts related to the implementation of a Service-Oriented Architecture (SOA) and a task to produce research-ready data sets.

Service-Oriented Architecture [WBS 3.2.3, 3.2.4, 3.2.5]. IRIS uses these same web services in its internal operations. In the past, internal applications accessed waveforms and metadata using a variety of legacy methods that had been developed over the DMC's lifetime. This practice grew the quantity and diversity of code needing maintenance. To make internal applications more efficient, manageable, and standardized, the DMC has been transitioning for several years to an SOA, implemented through web services (see WBS Element 3.2.5 above). Currently, most applications have transitioned to the same web services that are used to access data from the waveform repositories (i.e., real time and archive). The DMC will continue to transition to an SOA model for accessing waveforms and information in the Oracle database over the period covered by this proposal. Specifically, popular data access interfaces, such as WILBER, Breq_Fast, and jWeed, have been, or are being, transitioned to use web services. As software diversity decreases and efficiency improves through the leveraging of web services for both internal and external applications, DMC staff will be able to redirect their efforts toward new challenges.

Research-Ready Data Sets [WBS 3.2.3, 3.2.4, 3.2.5]. A major new DS thrust is to allow the scientific community to filter their data requests at the DMC through a set of customized parameters. Currently, researchers request data without the ability to specify data characteristics. The MUSTANG (Modular Utility for STAtistical kNowledge Gathering) Quality Assurance System (see WBS 3.2.6 for details) will be operational in 2014, and will automatically assess a variety of data characteristics and store the results in a Postgres database management system. The metrics will be available through web services to assist users in selecting data subsets with user-specified quality and/or other criteria.

DMC request servicing tools will be able to collate metrics determined by MUSTANG with user requirements and only

Table DS-1. Data product shipments from February 2010 through February 2011. The integrated development, management, and distribution of value-added products from the DMC are becoming an increasingly important activity.

Product	Count	Volume	Unique IPs
Back Projections	887	581 MB	165
Calibrations (IDA)	112	5.7 MB	49
EARS	630,756	54 GB	2,588
Earth Model Coll.	6,129	6 GB	1175
MT Trans. Functions	1,198	1 GB	29
Event Plots	40,968	375 GB	5,395
Event Bulletins	160	45 MB	79
Film Chips	136	807 MB	79
USArray GMVs	165,049	1.8 TB	28,141
Customized GMVs	108	377 MB	20
Moment Tensors	3,596	62 MB	1,156
Power Spectral Density	29	147 MB	8
TA Station Digest	59	229 MB	22
X-Product Bundle	1	2.4 MB	1

return time series that meet user-specified quality attributes. For example, a researcher working with a methodology that is gap-intolerant may simply request continuous data with a zero gap condition applied when requesting time-series data. Other request filters could also include, but are not limited to, signal-to-noise ratio over an event (or a subset of an event's seismic phases), data completeness, or seismometer mass position. Another aspect of the research-ready data sets initiative would allow users to retrieve data with a uniform instrument response, seismic component coordinate system, and sampling rate, even if the contributing data sources were not uniform in these characteristics.

By providing users with data filters, the data sets returned to the user will not require time-consuming post-request culling, will possess the optimal attributes for the researcher's studies, and will generally greatly reduce the amount of time each researcher must spend to achieve scientific results. In addition, the amount of data the DMC distributes to the end user may decrease, making DMC data delivery activities more efficient. A further benefit of this approach is that the DMS will be able to determine which parts of the archive are not usable by elements of the research community. Network operators may further use this information to help identify which stations need improvements in quality so that they can become more generally useful to the community.

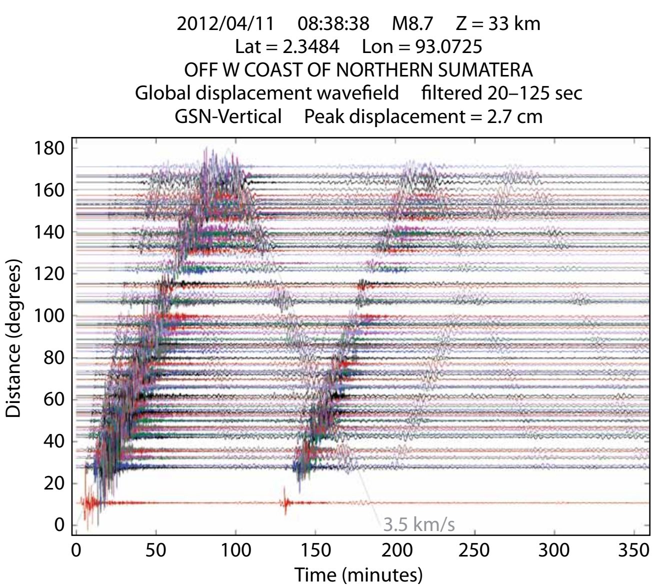


Figure DS-3. Interfering global displacement wave fields for the April 11, 2012, M8.6 and M8.2 Sumatra earthquakes recorded by the GSN displayed as a record section. Record sections are produced by the IRIS DMC within 2 hours after the onset of large events, but rarely would one see the wave fields from multitude M8 events. The short-arc Rayleigh wave (R1), major-arc Rayleigh wave (R2) and their multiple orbits are clearly visible across the entire surface of the Earth for both events. Peak vertical displacement exceeded 1 cm at all stations. Data are from the IRIS DMC. Additional automatically generated data plots for this event are available through the DMC's product management system, SPUD.

3.2.6. QUALITY ASSURANCE SYSTEMS

Analyst Data Examination. The best way to ensure high-quality data is by computer-assisted examination of the data streams by human analysts. Data Services will support analysts at the IRIS DMC to continue reviewing data quality of a subset of IRIS-generated data, such as those from the EarthScope Transportable Array. Data Services will continue to support quality-control activities at both GSN Data Collection Centers (at the University of California, San Diego, as well as the USGS Albuquerque Seismological Laboratory), and funds are requested to support these GSN Data Collection Centers (DCCs). DS will also continue to support international data centers that collaborate with IRIS to increase the open global availability of and access to data. This support will provide the Kazakh National Data Center in Almaty with the means to coordinate data collection and production of metadata for several networks in Central Asia. DS will continue to support activities at the University of Washington, with an emphasis on developing quality-control protocols that can be applied to the entire DMC archive, and in continuing to develop IRIS and Hyak high-performance computational facility partnerships at the host University of Washington.

MUSTANG Automated Data Quality Control. As the incoming data streams have grown in volume and their ultimate applications have become increasingly diverse, quality-control assessment strategies beyond human expert examination have become necessary. Data Services is thus developing an automated and versatile quality metric estimation system called MUSTANG. As time-series data enter the DMC in real time or in new data volumes, or when a newly delivered or existing component of the archive undergoes quality assessment, the MUSTANG system will efficiently and automatically apply quality metric processes to the specified data, with results stored in a Postgres database management system. All MUSTANG metrics will be openly available outside of the DMC for researchers, network operators, and other members of the seismological community.

The MUSTANG system's efficiency and flexibility are leveraged by past and ongoing software developments in web services. Networks that contribute their data to the DMC will thus be able to additionally monitor the quality of their network data by accessing MUSTANG quality metrics through efficient and user-friendly web service methods. DS will develop examples of quality monitoring applications and will work with network operators and the scientific community to ensure that the MUSTANG system provides access to community consensus quality metrics in a useful manner. These tools will be implemented across IRIS and applied to all IRIS-generated data (GSN, Portable Seismology, EarthScope) as well as data contributed by IRIS' partners around the United States and world (e.g., USGS, universities, and FDSN).

MUSTANG is being developed using a modular and service-oriented architecture that will provide standardized and customizable quality metrics to network operators and the scientific community. Resources will be assigned to the maintenance, extension, and performance of the MUSTANG system. Quality Assurance team members at the DMC will also be proactive in communicating quality concerns identified by the MUSTANG system to the network operators. These operators have the ability to address identified problems affecting data quality.

MUSTANG and associated community activities will allow IRIS to catalyze improvements in the data quality of US and international waveform and metadata managed by IRIS, primarily through performing automated procedures and working with network operators. Ultimately, we will work closely with the FDSN to promulgate the IRIS quality initiative to other data centers both within and outside of the United States. MUSTANG can never entirely replace human quality-control activities, but it is envisioned to significantly decrease the burden and cost of quality control by the start of this award while increasing its comprehensiveness and ultimate value.

3.2.7. EXTERNAL DATA COORDINATION

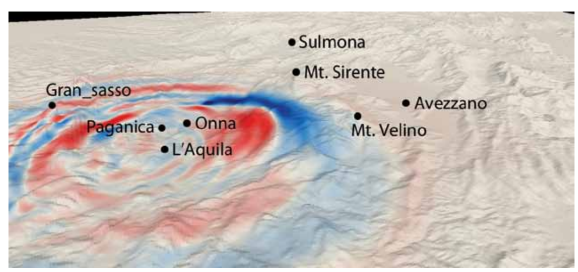
IRIS Data Services, along with International Development Seismology, hold active and important positions in external data coordination—their activities support external observing networks that manage and share information from non-NSF supported seismic networks in the United States and around the globe. There are three primary components of our external data coordination. The first involves support for metadata workshops hosted roughly every 15 months at convenient locations in Central and South America, Southeast Asia, and Africa/Middle East. Approximately 35 people from networks within each of these regions typically attend these workshops. The metadata workshops are closely coordinated with IDS Advanced Studies Institutes that occur immediately after metadata workshops, thus optimizing resources. The second component is the Regional Exchange of Earthquake Data (REED) activity that works with networks to support telemetry components, allowing data sharing in real time. REED also supports the transfer of data from field stations to network centers for hazard monitoring. The third component supports enhancements to the widely used SeisComp-3 network management software developed by the German Research Center for Geosciences (GFZ), now supported by the Potsdam GEMPA (Global Earthquake Monitoring, Processing, Analysis) group. Working with our FDSN partners, we identify new capabilities useful to SeisComp-3 users, and work with GEMPA to implement those capabilities. Most users of the SeisComp-3 system utilize it for the operation of seismic monitoring networks, but steps have been taken to also improve IRIS-brokered data availability from these networks to facilitate their broader scientific uses by the global research community.

An Earth Sciences Computational Center

Computing and numerical methods have progressed to the point that simulation has become an integral part of modern Earth sciences—particularly for seismology and geodynamics. The Transportable Array alone is providing so much data that analysis is keeping pace only for the computationally simpler methods, even as more demanding simulations are shown to improve the images derived from established methods such as ambient noise tomography (Tromp et al., 2010) and more computationally intensive analysis methods are being developed to extract additional information (Lin et al., 2012).

Fully exploiting Transportable Array and other geophysical data requires powerful numerical modeling tools, automation of routine analysis, and high-performance computing facilities dedicated to the meeting the requirements for Earth science research, which differ markedly from those in other fields. The need is a system structured specifically for the Earth science community simulation and imaging needs, configured to support user interaction between iterations in compute-intensive inversions as well as long run times, with large fast storage capacity, large memory, and many cores (Rietmann et al., 2012). A broad range of Earth scientists—involving IRIS, CIG, SCEC, CIDER, and DOE National Laboratories – have started discussions with NSF and other federal agencies about establishing an appropriate capability.

This proposal does not request support for high-performance computing of the scale that is required, but the data resources of the DMC and the nascent activities in cloud computing proposed for Data Services could be closely integrated with an initiative to develop an Earth sciences computational center.



A snapshot of the seismic wavefield for the April 6, 2009, L'Aquila earthquake—computed with a high-performance cluster using the Spectral Element Method—shows the influence of topography and variable Moho depth, as well as source effects. These high-frequency simulations, which are accurate up to 5 Hz, may be used to assess the response of engineered structures and may guide the development of better seismic building codes. *(Peter et al., 2011)*

3.3. EDUCATION AND PUBLIC OUTREACH

Program Description

The IRIS Education and Public Outreach (EPO) program is committed to advancing awareness and understanding of seismology and geophysics while inspiring careers in the Earth sciences. The program draws upon the rich seismological expertise of IRIS Consortium members and combines it with the educational and outreach expertise of the program staff to create products and activities for a wide range of audiences. Although relatively young when compared to the other IRIS programs, EPO has established itself as a model educational initiative among NSF-funded programs and has made significant impacts in a variety of arenas. Examples range from creating real-time seismicity displays for millions of Web users, visitor centers, and museum visitors, to contributing to the development of the Earth science workforce through a highly competitive summer research program for undergraduates. The guiding principles of the EPO program are to deliver programs, products, and services that:

- Target a range of audiences, including grades 6–12 students and teachers, college students and faculty, researchers, and the public
- Emphasize seismology and the use of seismic data
- Benefit IRIS through broader impacts to students and society or through services supporting members' needs
- Undergo continuous improvement, leveraging both internal and external evaluations of products and programs
- Promote increased participation of underrepresented groups
- Maintain high levels of scientific accuracy while employing best educational practices

The program's recently updated strategic plan includes a set of broad goals that underpin the ongoing and new initiatives in this proposal. These goals include:

Figure EPO-1. The Active Earth Monitor kiosk

- ***Improve Seismology Education.*** Increase the quantity and enhance the quality of seismology education
- ***Expand Earth Science Awareness.*** Expand opportunities for the public to understand and appreciate seismology
- ***Support Consortium Members.*** Provide education and outreach products and services for members of the IRIS community
- ***Expand the Earth Sciences Workforce.*** Support development of a larger and more diverse Earth science workforce

These goals allow the program to maintain successful programs in grades 6–12 and informal education while emphasizing new development efforts aimed at undergraduate instruction, and workshops and training for the IRIS community. EPO will also expand its support of broader IRIS activities, particularly through closer involvement with Data Services and International Development Seismology.

Program Impact and Educational Justification

- There were over 6 million visitors to the IRIS website in the past year
- There have been over 1 million total visitors to the IRIS YouTube channel
- There were over 500,000 hits to the Recent Earthquake Teachable Moments pages in the past two years
- 21 IRIS/SSA Distinguished Lecturers have given over 117 presentations to public audiences
- Over 1200 teachers and college faculty have attended one-day or longer IRIS workshops
- Over 420 users of educational seismographs from 37 states and 18 countries have registered their station in the Seismographs in Schools database
- 126 undergraduates have engaged in summer internships, with 90% of surveyed alumni who have completed their undergraduate degree in a geoscience career or graduate schools

Recent Earthquake Teachable Moments. Newsworthy earthquakes can capture the attention and imagination of students, however, many instructors lack the time and/or background knowledge to synthesize available Web materials into a coherent package that tells an educational story. By delivering timely, easy-to-use resources following major (M≥7) earthquakes, the Teachable Moments presentations enhance Earth science education by expanding classroom discussion of seismology concepts and tectonic processes. The presentations are generally posted to the IRIS website within 24 hours of the event and are produced in collaboration with the University of Portland. Presentations contain interpreted USGS tectonic maps and summaries, animations, visualizations, and other event-specific information. Each presentation is formatted to

Figure EPO-2. A new Welcome Center on Interstate 55 near New Madrid, Missouri includes an Active Earth Monitor connected to the Internet and signage about EarthScope, the USArray Transportable Array, and the region's earthquake history that were provided by IRIS. The Welcome Center was designed with an earthquake theme, including the regional seismic hazard map built into the floor.

allow an educator to tailor the materials to their particular audience, and the presentations are also available in Spanish.

Professional Development for Teachers and College Faculty. Most middle and high school Earth science teachers have minimal science background in plate tectonics and seismology. To address this need, EPO offers a variety of professional development opportunities for teachers. Constructed to directly support lesson plans and other resources developed by IRIS or others, these workshops improve teachers' seismological content knowledge and pedagogical skills, and model use of appropriate curricular materials to enable teachers to effectively implement the activities. Professional development opportunities range from one-hour sessions at regional and national science teacher or informal educator conferences, to multiday workshops, often offered in partnership with other organizations.

Public Displays for Museums and Other Venues. Informal science venues are an important mechanism for scientific outreach to the general public, and the display of real-time seismic data offers the opportunity to capitalize on visitors' enthusiasm for current information. As an outgrowth of our experience creating large custom museum displays, including surveys of audience response (Smith et al., 2006), IRIS developed the Active Earth Monitor to provide a way to engage audiences in smaller venues (Figure EPO-1). These displays have been installed in locations ranging from visitor centers in national parks to small museums, schools, and departmental lobbies in universities. Packages of user-selected content pages, including general seismicity, and the seismic and tectonic settings of Cascadia, the Basin and Range, and New Madrid have been developed in collaboration with UNAVCO, the EarthScope National Office, the University of Memphis (Figure EPO-2), and others.

Web Resources, Animations, and Social Media. The IRIS website is the face of the Consortium to the general public, and a key goal is to provide content that brings users back to the site (Figure EPO-3). This includes featuring timely information about recent seismological events as well as longer-lasting information such as classroom activities and animations. IRIS also maintains a range of social networking channels spread over a variety of entities, including Facebook, Twitter, and YouTube to complement the website and engage additional users.

Animations can make unfamiliar science concepts more accessible to students, and the dynamic nature of over 100 IRIS animations helps engage the current generation of students. Accompanying video lectures both promote Earth science teachers' grasp of new science content and support their classroom presentation of earthquake science. Most of the animation and video lecture sets also have links to classroom activities that promote active learning of key seismological topics.

IRIS/SSA Lectureship. There is a strong demand at informal learning institutions like science museums and science cafes to provide local communities with direct contact with distinguished scientists. To help meet this need, two IRIS/SSA speakers are selected each year to convey both the excitement and the complexities of seismology to a general audience. To expand the number of viewers, most lectures are also placed online. The impact of the Lectureship Program is further increased by having many venues arrange additional events in

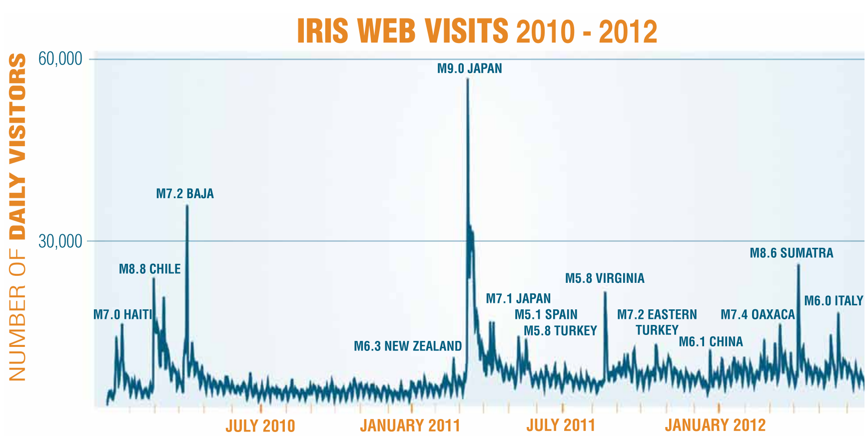


Figure EPO-3. Daily IRIS web pages visits, 2010–2012. The the increase in traffic after an earthquake results in both a short-term peak and a long-term increase in users, as new users continue to come back to the site.

Figure EPO-4. IRIS summer research interns set up a PASSCAL Geode during the intern orientation at New Mexico Tech.

conjunction with the lectures, such as webcasts, radio interviews, and teacher workshops.

Summer Internships for Undergraduates in Seismology. Since its inception in 1998, the IRIS Undergraduate Internship Program has provided undergraduates with the opportunity to work with leaders in seismological research and to produce research products worthy of presentation at large professional conferences. Capitalizing on the Consortium's distributed, yet extensive host pool, students are exposed to research opportunities across the full spectrum of seismology (Figure EPO-4). Since 2006, this program has been jointly funded through three NSF Research Experience for Undergraduates (REU) site awards and through the IRIS core award. REU funding supports student costs, while the IRIS core funding supports infrastructure such as salaries and other oversight costs.

Proposed Activities: Bringing Seismology to a Wider Audience

EPO has reached a level of maturity and recognition within the Earth science education community where it can leverage its educational resources to greatly expand its audience, while still maintaining the core activities described above. EPO is also poised to provide more assistance across the Consortium, including documenting best practices of portable and permanent seismic networks, and working with International Development Seismology to reach a wider international audience. Five key areas are targeted for expansion in this proposal, and are described in the following sections:

- *New Instructors.* Providing integrated online curriculum and professional development for teachers and college faculty
- *New Undergraduates.* Developing targeted undergraduate programs, with an emphasis on Educational Affiliates
- *New Classrooms.* Expanding the number of classrooms teaching seismology, with new sensors, software, and support resources
- *New Generation of Information Consumers.* Providing interactive content for mobile devices and enhanced Web access across all platforms
- *New Support for IRIS-Wide Activities.* Expanding the reach through cross-program activities

As the EPO program implements these new initiatives, the resulting programs and products will be subject to continuous evaluation and improvement. To ensure the most effective use of both time and financial resources, EPO activities will continue to be evaluated via a combination of both internal and external assessments. Results from these assessments inform the program's decision-making process, allowing IRIS to significantly enhance its EPO activities over time.

3.3.1 AND 3.3.2. MANAGEMENT AND GOVERNANCE

The EPO Standing Committee, which has expertise in seismology as well as education and outreach, provides oversight and community input for EPO program activities and strategic direction. The EPO Director manages EPO program staff, consultants, and small limited-term subawards outlined in each WBS element. The Director also ensures the integration of EPO activities with other IRIS programs, and fosters collaborations with other organizations.

3.3.3. EDUCATION AND PROFESSIONAL DEVELOPMENT

New Middle School, High School, and Undergraduate Instructors

While there will continue to be a need for in-person professional development, IRIS resources will be used by many more educators through the creation of an integrated system of online professional development and access to resources. The IRIS: InClass project is an online portal that combines and adds value to existing IRIS resources (e.g., activities, professional development workshops, posters, animations/video clips, data, software), and increases access to these resources while also improving the reach and impact of individual components. Key elements include:

- Pedagogically sound learning sequences that combine resources together in a way that adds value to each individual piece by scaffolding student learning of individual concepts
- Online video and text-based professional development that supports educators' use of the learning sequences
- A portal that allows users to discover additional resources that are closely related to those that the user was initially seeking

The elements of the InClass portal will be linked to other resource sites, particularly Carlton's Science Education Resource Center for undergraduate resources. The value added by the InClass site is the sequencing of a smaller number of topics, with links to all the associated resources, including video clips explaining the rationale behind each sequence.

New Undergraduates

Curriculum. Closely related to the development of the online learning portal is the development of new undergraduate resources by leveraging the talent and resources that are available within the Consortium membership, and making those resources available to a wider audience. IRIS will also build on modules that are nearing completion that are based around *Seismological Grand Challenges in Understanding Earth's Dynamic Systems* (Lay, 2009). The objectives of this collaborative Course, Curriculum, and Laboratory Improvement project (with The College of New Jersey) include the creation of undergraduate instructional materials that correspond to each of the Grand Challenges, as well as six inquiry-based laboratory activities. Seismology faculty will also be invited to share their own rough exercises via a "faculty only" area on the IRIS website. IRIS will assist in editing the submitted materials to make them more easily usable by other faculty, and will offer a small stipend annually to a faculty member who is interested in devoting one to two months of time to creating and editing resources. EPO will also conduct workshops with undergraduate faculty to vet, improve, and disseminate these new materials.

A collaboration with the InTeGrate project, a major five-year multi-institution program led by Carlton College to improve undergraduate geoscience education, will expand the reach of IRIS materials even further. IRIS will lead the effort to create introductory geoscience modules for upper-level students in other sciences, math, and engineering.

Two-Year Colleges. Over 50% of recent Bachelor of Science degrees in geoscience were awarded to students who attended two-year colleges (Houlton et al., 2012), and thus this is a critical audience to reach to expand awareness of Earth science and to reach potential geoscience majors. EPO can use its linkages to address this need by engaging the two-year college community and fostering partnerships with universities. This approach will include working with the National Association of Geoscience Teachers, and increasing the number of IRIS Educational Affiliates, for whom we will provide specially designed workshops as well as travel to IRIS workshops, and travel to research universities to enable collaborative research.

Involve More Undergraduates in Field Research. Each summer, numerous efforts to collect seismological data are underway within the IRIS community and most such experiments have a need for field assistants. To help fill this need, EPO will develop a recruitment tool for undergraduate field assistants. This clearinghouse will also provide opportunities for students not currently part of the IRIS community, including math or physics students who might have an interest in seismology but have never taken a course or participated in fieldwork, or two-year college students who do not have the prerequisites for an IRIS internship. EPO will ensure that the field assistantship is more than just manual labor by providing a structured PI application process that requires PIs to provide some related learning experiences for the field assistants.

New Classrooms

Expanding the use of seismic data in middle school through college classrooms requires not just easy access to data, but also robust ways for students to collect their own data, and intuitive analysis tools. Seismological observations are the one direct measurement that students and teachers can make from their location that reveal Earth's interior dynamics. Based on 10 years of experience of supporting seismographs and providing data to schools, EPO has a goal of creating quality educational resources such that there are:

- Hundreds of high-sensitivity sensors in classrooms to record global earthquakes
- Thousands of USB and other motion sensors to teach the basics of ground motion
- Hundreds of thousands of students using IRIS data via the Web in classroom activities

While in the past EPO has focused primarily on one educational sensor for recording one's own data, over the next five years the emphasis will be on providing recording and analysis software that will support multiple sensors. This will increase the availability of sensors and allows IRIS to focus on providing online resources for sharing data from

Coordinated IRIS, UNAVCO, and ESNO Education and Outreach Activities

The UNAVCO Education and Community Engagement and IRIS Education and Public Outreach programs have collaborated extensively over the past seven years and it is proposed to continue the successful partnership. The partnership has been particularly valuable for EarthScope-related activities, where UNAVCO and IRIS work closely with the EarthScope National Office (ESNO) to bring EarthScope science to national, regional and local audiences within the EarthScope footprint.

Collaborations have ranged across each group's products and services, including:

- EarthScope-focused teacher workshops
- EarthScope interpretive workshops for informal educators (led by ESNO)
- Development of content for the IRIS Active Earth Monitor
- Preparing PBO-, USArray-, and EarthScope-focused materials on topics such as episodic tremor and slip for wider distribution through print, Web, and mobile information technologies
- Cooperation on diversity initiatives, including research experiences for undergraduates, and shared booths and student field trips at professional meetings that promote diversity

Coordination is further enhanced through the E&O advisory committees of EarthScope, IRIS, and UNAVCO, with ex-officio participation in each by the three program directors.

Developed jointly by UNAVCO and IRIS.

educational sensors and coordinating local and regional support efforts for teachers.

IRIS experience with seismometers in schools has shown that ongoing support is an important element for success. The best way IRIS can expand the adoption of classroom sensors to hundreds of new classrooms is to work with and train regional network coordinators who then provide support to classroom teachers in their area. This approach has already been successful in such areas as Boston and Michigan, and will be expanded over the next five years. This expansion will be driven in part through collaboration with NASA's newly announced InSight mission to land a seismograph on Mars. IRIS will provide the public access to the Mars seismograph data and is one of the lead subawardees for the EPO program focused on engaging students in the use of Mars seismic data and its comparison to earthquake data.

The educational software suite to support the use of seismic data is defined such that each independent application contains a wide enough set of features so that most educational activities require using only one application. The primary applications are:

- IRIS Earthquake Browser. IEB, developed by the IRIS DMS and now being modified for educational users, allows users to explore seismicity data via a Google map-based interface. Results of customized searches are displayed on the map and will be viewable in an integrated pseudo-3D viewer.
- jAmaseis. The primary function of jAmaseis is to view and locally store data from educational seismographs. Nearly completed enhancements to jAmaseis will allow the data to be shared in near-real time with other schools, will display near-real-time data feeds from the DMS, and will continue to integrate with the online international Web database developed and maintained by IRIS (Figure EPO-5).
- SeismicCanvas. This new application will be aimed mainly at undergraduate instruction and will have the primary goal of allowing easy use of DMS data sets in classroom and lab exercises. This application will include the ability to access, display, and manipulate waveform data and record sections with a very short learning curve.
- QCN/MEMS. The software developed in collaboration with the Quake Catcher Network (QCN) will support the use of MEMS accelerometers in classroom activities, including the display and recording of single- and multiple-component waveform data from individual and multiple sensors.

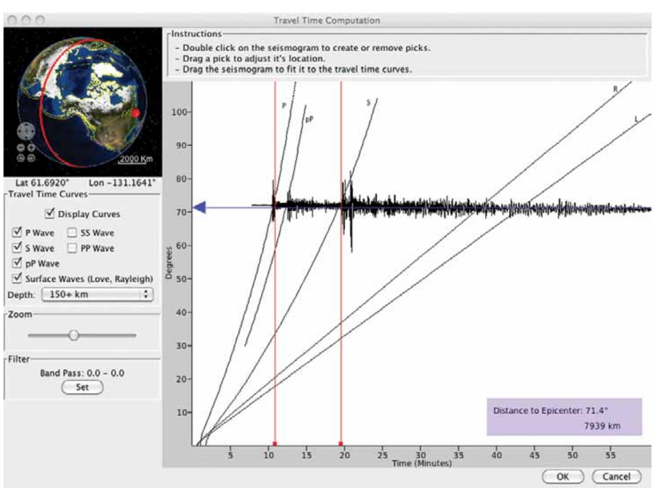


Figure EPO-5. jAmaseis will contain graphical analysis tools for K–12 exercises including epicentral location and magnitude determination.

The DMS has recently developed a rich set of automatically produced data products and many of these products can be used for educational purposes, particularly at the undergraduate level (e.g., ground motion visualizations, record sections, back-projection movies). However, for nonseismologists, some context and instructional materials are needed, and we propose to create classroom PowerPoints and instructor guides to accompany the data products.

3.3.4. WEB, MOBILE DELIVERY, AND PUBLIC DISPLAYS

New Generation of Information Consumers. Smart phones and tablet computers are becoming primary Web information tools, and it is critical that IRIS provide information in a form that can be accessed from these devices. Over the next five years it will also be important to evaluate and adapt efficiently to new methods of information dissemination as they become available, whether it be new mobile devices or new modes of social networking. Resources will include simplified near-real-time information pages for mobile devices, new animations and videos, and educational materials that involve the motion sensors in most new devices. Mobile apps highlighting IRIS data products will also be developed to complement existing Web tools.

Use of social media will be expanded, building on experiences in the past two years, where a consistent following on Facebook has developed. The goal is to attract audiences already using those venues and to draw them to the main IRIS website for more detailed content. Targeted input will be provided to articles on Wikipedia via a collaboration with the Seismological Society of America, adding content to seismology-related material where appropriate.

EPO is proposing to increase cross-program support for access to web-based products. For example, DMS web services provide very flexible access to data for seismologists, but a simplified graphical interface for educational users, with a target audience of undergraduate and two-year college geoscience instructors, will greatly expand the potential userbase. EPO will also provide web developer support for other programs, particularly International Development Seismology.

While permanently mounted computer-monitor-based displays are the most common public display technology, and thus were the initial focus for Active Earth Monitor content, new content will be designed to be platform-independent with the ability to run on a variety of devices (iPad, tablets, smart phones, widescreen HD touch display panels), along with multitouch capability.

3.3.5. OUTREACH

New Support for IRIS-Wide Activities

Workshops and Training for the IRIS and International Community. EPO has extensive experience planning and implementing high-quality professional development experiences for teachers and non-IRIS Consortium college faculty. As part of the strategic plan goal to support IRIS Consortium members, EPO proposes to combine that experience with IRIS community research and education expertise to work with other IRIS programs to provide workshops designed for Consortium graduate students and early career faculty that are more data intensive. An example of such a workshop is the USArray data processing short courses held in 2009–2011. Another workshop for IRIS researchers and students will focus on shallow active-source seismology, supporting the acquisition of new equipment by by the Portable Seismology program. In addition, EPO will work with International Development Seismology to provide educational materials and to provide support for capacity-building workshops, building on their successful Advanced Studies Institutes conducted in 2011 and 2012. This support will include the development of an online data processing library that will consist of software and sample data sets used in the short courses and the advanced studies institutes.

Documenting Best Practices. As a global leader in scientific data collection and dissemination, it is imperative that IRIS maintains a leadership role in aiding the community with best practices in the technical, operational, and training aspects of seismic data collection. To do that requires the creation of online documentation for such topics as installation and management of portable (PASSCAL), temporary (Transportable Array), and permanent (GSN) seismic networks. In addition, generic materials will be developed to assist in outreach for PI-led portable experiments, both within the United States and internationally. For these documents to be widely used will require training, as well as facilitating the inclusion of international partners.

Transportable Array Siting Outreach. Support for siting and deployment of the Transportable Array is tightly integrated with other EPO activities. Future activities will include interaction with university, local, regional, national, and international media to inform audiences about the Transportable Array and EarthScope; preparation of newsletters, information sheets, and other publications that provide information about the status and scientific findings from the project; and participation in technical meetings and exhibitions to share information about the Transportable Array with the scientific community. TA outreach and related educational activities in Alaska will involve working closely with Alaskan partners to leverage their experience and connections with teachers, students, and the general public, particularly native groups.

3.4. COMMUNITY ACTIVITIES

Description

Community Activities are an essential part of managing the IRIS facilities, keeping the Consortium membership and facility users aware of the resources available to them and providing various forums for communication and sharing of ideas. Some examples of Community Activities include:

- Supporting broad community governance to ensure that ongoing services continue to meet quality and relevance criteria, and develop initiatives as needs emerge
- Convening events both for the broad community to survey the range of services and science, and for community sectors to delve into specific aspects
- Forming ad hoc working groups and committees to focus sustained attention on critical issues in a timely manner
- Promoting ongoing communication among seismologists, policy specialists, and other professionals by participating in coalitions and events, maintaining the IRIS website, and distributing bulk email and publications
- Providing a framework and resources to “Early Career Investigators” to allow them develop a suite of special-interest services

Community Activities interacts with other national and international associations and academic consortia at the highest levels, exploring initiatives and programs advantageous to the community, interacting with other organizations that manage geoscience facilities, and advocating for investment in geoscience research and education. The IRIS Board of Directors initiates and monitors these activities, and works closely with facility governance committees to explore issues specific to the various services and synergies among them.

The free and open exchange principles under which IRIS provides seismological services have engendered a supportive culture. It is common for geoscientists and multidisciplinary groups to use facility governance bodies as a framework to develop community initiatives, leverage individual programs, identify international partners, and meet educational and outreach objectives of individual projects. Conversely, NSF calls on the collective facilities management to convene meetings and workshops that permit the community of seismologists and related investigators to prepare for new initiatives that are beneficial to geoscience investigators whose interests extend far beyond services supporting seismology. Important recent examples include:

- A community workshop on a long-range science plan for seismology, followed by preparation and production of *Seismological Grand Challenges* (Lay, 2009)
- A series of meetings among diverse groups to develop a community consensus on hosting an OBSIP Management Office to coordinate national resources in portable ocean bottom seismology

Seismological services are global by definition and have been international in practice. The GSN’s global scope rests on a foundation of international partnerships and agreements. PASSCAL experiments have been performed on every continent, usually in partnership with local university and government collaborators. The DMS participates in data-exchange agreements with other networks in the FDSN. This global geographic scope demands international credibility arising partly from Community Activities’ generous cooperation to enable international scientific collaborations on large and small scales.

Proposed Activities

Community Activities engage the seismological community, the broader geoscience community, and science agencies through the governance structure, meetings, and publications. This structure ensures the continued quality of and support for individual research projects by IRIS services.

3.4.1. WORKSHOPS

Infrastructure and Research In Seismology Workshops. The biennial IRIS Workshops are an enormously popular and effective way to bring together practitioners from many disciplines of academic seismology and a broad geosciences community to review programs and services, plan new initiatives, and stimulate interactions among individuals, research institutions, and government agencies. The Workshop structure includes plenary science sessions in themes developed through the facility governance, poster sessions organized around clusters recognized among openly solicited contributions, tutorials on using services, and small self-organized working groups on a wide range of topics.

Figure CA-1. More than 237 participants gathered June 12–15 in Boise, ID, for the 2012 Workshop—IRIS: The Next 25 Years—at which plenary themes included: Science Drivers and Enablers; Imagine–Anticipated Science to Meet New Challenges; New Technologies and Media; and Facilities for the Next 25 Years.

The IRIS Workshop now extends to aspects of seismology beyond earthquakes, anthropogenic sources, and deep Earth processes to the societal impacts of seismology unique to developing countries, cryospheric and other polar studies, marine geophysics supported by OBSIP, and atmospheric science studies that use data from Transportable Array environmental sensors.

Participation in the workshop has continued to be strong, even as demands on the time of faculty members and researchers have grown. As requested by NSF, the IRIS Workshops will alternate yearly with the EarthScope National meeting.

Seismic Instrumentation Technology Symposia. In 2009, IRIS initiated biennial "Seismic Instrumentation Technology Symposia" in collaboration with the USGS, DOE, and NEES to facilitate communication among academe, federal agencies, and industry with common or overlapping interests in observational seismology. These symposia are more focused than the larger IRIS Workshops, emphasizing exploration of emerging technologies that provide solutions to key technical challenges in sensors and data acquisition. The evolving needs of network and field operators are highlighted, as well as emerging trends in communications, power, and timing. Are the current scientific objectives for data quality, timeliness, bandwidth, and dynamic range being met? Can logistical and operational burdens be addressed more efficiently?

Speakers from different user communities—permanent observatories, portable and transportable experiments, ocean bottom deployments, regional networks, strong motion, structures—offer perspectives on tasks that are difficult or expensive to accomplish and new capabilities that they are seeking. Manufacturers give brief presentations and engage in individual conversation at their posters. Scheduling these symposia in alternate years from the IRIS Workshops sustains mutual awareness of scientific requirements and technological developments.

3.4.2. PUBLICATIONS

Annual Report. By combining coverage of both seismological services and examples of the science that they facilitate, the IRIS Annual Report has been effective at demonstrating the benefits to the nation from infrastructure to facilitate seismological research. The audience for this popular report extends far beyond the principal investigators who benefit directly from the services, and includes undergraduates and graduate students who participate in the projects, educational and foreign affiliates who collaborate with the PIs, government agencies that provide funding or form academic partnerships to carry out projects, and science policy professionals.

Annual Brochures. Each year, "IRIS-at-a-Glance" summarizes the status of seismological services and the facilities that enable them. It is a quick-to-read reference that informs users, supporters, and even legislators.

Figure CA-2. Examples of recent IRIS publications.

Science Highlights. A newly started collection of graphically oriented précis, these highlights showcase the extensive body of work produced by the community and illustrate the science that is enabled by seismological services. Each highlight is structured around a comprehensive, key visual that is combined with a short caption in a format is conducive to display in categorized galleries. The goal is an image and explanation for broad audiences of geoscience professionals.

EXHIBITIONS FOR POLICY MAKERS

Annual Congressional Exhibitions organized by the Coalition for National Science Funding, the Coalition for the US Geological Survey, and other groups represent recurring opportunities to inform legislators about the national benefits from research in seismology and other geosciences. In addition, occasional ad hoc Congressional exhibitions, such as the NSF Natural Hazards event, provide further opportunities to inform at the leadership level. An organization that both reflects the community and manages linked services is uniquely capable of putting on an exhibit that offers full information extending from facilities to science accomplishments and broader impacts.

PAN-IRIS COLLABORATIONS

One of the themes of this proposal is to enhance the documentation and dissemination of IRIS best practices for the benefit of other organizations, especially in education and the international development sphere. The resources for developing these materials lie within the programmatic budgets, but Community Activities will assist in dissemination of these materials at workshops, through pan-IRIS publications and in other national and international venues.

3.5. INTERNATIONAL DEVELOPMENT SEISMOLOGY

Overview

International Development Seismology (IDS) is IRIS' newest initiative. Its mission is to coordinate and facilitate program and community activities in developing countries. With the US seismology community directing its focus toward global-level, multidisciplinary scientific inquiry, IDS contributes to and draws from all aspects of IRIS facility operations. Although seismology has always been a global science, recent technological advances have greatly enhanced seismologists' ability to address questions requiring large-scale, high-precision observations that were not possible even just a few years ago. Given this reduction in technical constraints, two factors emerge as limiting accelerated scientific progress in developing countries: (1) the number of scientists, engineers, and technicians able to participate in seismology projects, and (2) the availability of financial resources to sustain large-scale international projects.

Active participation of strategic, operational, and scientific collaborators from other countries in international projects leverages US research investments, and ensures the sustainability of observatory facilities. These long-standing productive partnerships have made possible some remarkably successful international projects such as the Global Seismographic Network. However, the availability of scientifically and technically able partners is often limited in developing countries, but can be substantially increased through education and training. While technological absorptive capacity varies widely among developing regions (Latin America, Southeast Asia, Africa, Middle East), many developing countries count on groups of interested individuals who have sufficient technical and scientific background to become potential collaborators and invaluable partners to leverage and facilitate US-initiated scientific projects. In most cases, engaging these potential partners requires investments in activities specifically designed to disseminate best practice principles and modern research techniques. This need for training spans the full spectrum of seismological research, from the technical aspects of network installation, management, and maintenance, to data acquisition, sharing, and analysis. Investment in building seismological capacity in developing countries is not only essential for sustainability of international science projects but also reflects proper stewardship of research funds, leveraging investments in research facilities.

In addition to expanding the international scientific community, the increased ability to pursue global-scale science presents the seismology community with the opportunity to substantially increase data return and to raise seismic hazard awareness in developing countries, particularly in regions of the world with large dense populations. Increased hazard awareness has the potential to guide mitigation policies, leading to local government investment in national seismic hazard monitoring and support for coordination with the international seismology community. Moreover, increased focus on geophysical hazards in developing regions also has the potential of increasing investments in analysis of underlying phenomena by private and nongovernmental organizations, further leveraging US scientific investment.

The breadth of actions needed to facilitate seismological research in developing countries overlaps with those actions needed to support general economic development and sustainability. These actions include: (1) expanding scientific and technologically competent workforces, (2) increasing seismic hazard awareness, leading to risk reduction strategies for housing and civil infrastructure, and (3) discovering natural resources. This overlap presents IRIS with the opportunity to support these activities via partnerships with a diversity of US, foreign, and international stakeholders, leveraging US scientific investment. The success and sustainability of these leveraging schemes will depend on the pursuit and development of appropriate and productive partnerships, and on the design of programs that satisfy all stakeholders' missions and objectives. Figure IDS-1 illustrates the rationale for supporting seismological research through seismic hazard awareness and workforce development, leading to increased foreign and international investments, leveraging US research funding.

IDS Background and Accomplishments

IDS addresses the IRIS community's recognition that education and training are fundamental to the advancement of geophysics around the world. Because activities related to seismology in developing countries are distributed across the breath of IRIS programs, the IRIS Board of Directors appointed the International Development Seismology Committee and hired the Director of IDS to coordinate efforts among the IRIS programs, and with external organizations. Since 2009, IDS activities have spanned a broad spectrum, including exploratory meetings, collaborative projects, multidisciplinary activities in response to destructive earthquakes, and international capacity-building activities.

Exploratory Meetings

Over the past three years, IRIS has conducted a series of meetings designed to identify and engage partners in developing countries who share IRIS' vision and who are interested in collaborating with the IRIS community in increasing seismological research capacity. These have included a meeting between the IDS Committee and representatives from CERESIS (Centros Regionales de Sismologia en America del Sur) member countries in Lima, Peru, in October 2009; the workshop "Geophysical Hazards and Plate Boundary Processes in Central America, Mexico and the Caribbean: A Workshop to Build Seismological Collaboration and Capacity" in Heredia, Costa Rica, in October 2010; and the ALMAS (ALianza MesoAmericana de Sismologia, ALliance MesoAmericaine pour Siesmologie, ALliance for Middle America Seismology) meeting in Rio Grande, Puerto Rico, in February 2011. The common findings of these meetings have been the recognition of the heterogeneity of conditions that impact geophysical research as well as earthquake monitoring and preparedness among individual countries, and the need for intense, focused effort on professional and scientific training.

Capacity Building

In response to these identified needs, IRIS has conducted a variety of training activities to enable open data sharing and regional networking for seismologists who will be in positions of leadership in foreign earthquake hazard mitigation programs. These activities have included metadata workshops organized by IRIS Data Services in Kuala Lumpur, Malaysia (2008), Cairo, Egypt (2009), Foz do Iguaçu, Brazil (2010), and Bangkok, Thailand (2012), and research-focused Advanced Studies Institutes in Quito, Ecuador (2011, funded by NSF OISE), and in Bangkok, Thailand (2012), in coordination with the metadata workshop.

Collaborative Projects

Conducting research in developing countries presents challenges and rewards, particularly when these projects are led in collaboration with local partners. The optimal scenario for these international projects includes cost sharing from the corresponding national government. A model scheme for these collaborations was developed following the February 27, 2010, M_w8.8 Maule earthquake in Chile. IRIS worked with scientists from US universities and the University of Chile on the deployment of 58 portable instruments funded by an NSF Rapid Response Research (RAPID) award, making all data freely open and available. This initial study, which built on long-standing collaboration between US and Chilean researchers, was further extended with the initiation of a joint plan to upgrade national and global observations in Chile.

Multidisciplinary Activities in Response to Destructive Earthquakes

Haiti's earthquake on January 12, 2010, presented numerous challenges to the science and engineering communities, government agencies, and nongovernmental organizations. In light of these challenges, IRIS organized the workshop "Rebuilding for Resilience: How Science and Engineering Can Inform Haiti's Reconstruction" upon the request by the National Science and Technology Council Subcommittee on Disaster Reduction. This international, multidisciplinary and cross-sector workshop was cosponsored by the US Department of State, USAID, and the United Nations Office for Disaster Risk Reduction, and was funded by NASA, NSF, and the USGS. It was held at the University of Miami on its Coral Gables, Florida, campus, establishing a model for multiagency support of transitional activities.

Scientific Impact

Proper characterization of Earth dynamics and earthquake mechanisms requires global seismic data coverage. While seismic station coverage in North America and Europe has increased tremendously in recent years, collection of research-quality data continues to lag in Central and South America, Africa, the Middle East, and Central and Southeast Asia because countries in these regions have limited resources to invest in seismological infrastructure, education, and training. IRIS has long been a leader in enabling US investigators to conduct research in these regions through various programs, and in enabling foreign collaborators to contribute to global seismological research. Examples of these international projects include (1) nearly 100 temporary deployments in developing countries and 18 deployments in China supported by PASSCAL, providing students in developing countries with opportunities for in-country training and access to US graduate programs in seismology; (2) over 60 GSN seismic stations deployed in developing countries, in close coordination with in-country hosts; (3) increased availability of seismic data from developing countries through dissemination of the use of standardized data formatting protocols, and by helping local seismic station operators with infrastructure for real-time data transmission through the DMS Regional Exchange of Earthquake Data (REED) program; (4) installation of 10 permanent backbone geophysical observatories, including

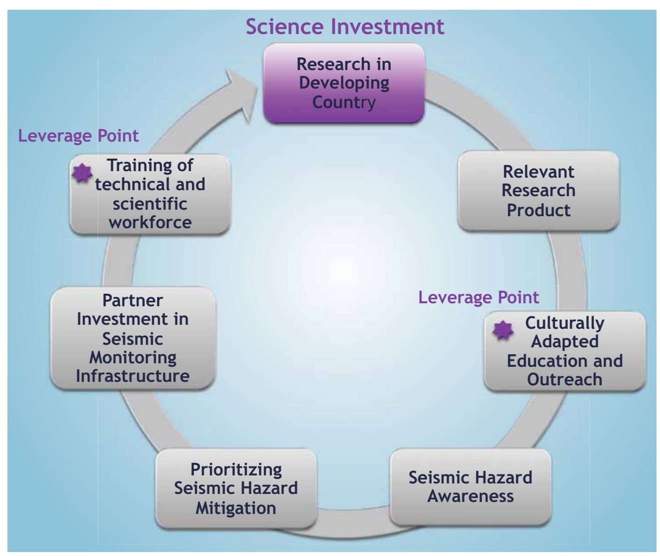


Figure IDS-1. Multiple interdependent elements are necessary for successful global-scale or international projects involving research in developing countries. Strategic investments in education, public outreach and training are likely to lead to diversified stakeholder engagement, including local governments, leveraging US scientific investment.

broadband seismic stations in Chile, supported by the NSF MRI and in partnership with the University of Chile; and (5) the international aftershock deployment of 140 stations following the M_w8.8 2010 Maule earthquake, partly funded by the NSF RAPID award, that led to the International Maule Aftershock Deployment data set that is open to the community.

3.5.1 MANAGEMENT

IDS is managed by the IDS Director who is responsible for the implementation and cross-programmatic pan-IRIS coordination of these activities, as described in the linked WBS elements below. In addition, the IDS Director facilitates administrative and logistic support to other international activities initiated by the GSN and PASSCAL, including interaction with the Department of State and US embassies in project host countries. The director also supports and facilitates the engagement of IRIS members in these countries, assisting with coordination with the local academic, scientific, and technical communities. One assistant supports the director's activities.

Oversight for IDS priorities and activities is provided by the IDS Committee appointed by the Board of Directors, and by IRIS standing committees on activities relevant to their respective Programs. The IDS Committee meets in person once a year and maintains periodic online and teleconference communication.

Coordination Among IRIS Programs

Over the next decade, IRIS programs will continue to evolve in support of increasingly larger-scale international research projects. The IRIS mission of facilitating seismological research will require addressing the two emerging science-limiting factors: increasing the number of competent seismologists worldwide—particularly in developing countries—and securing resources to support operational facilities on a global scale. IRIS will undertake a pan-IRIS approach to both challenges through implementation of capacity-building activities covering all aspects of seismological practice, and through the development of concerted strategies to secure funding to leverage NSF investment in seismological facilities. These programs and activities will be integral to relevant IRIS programs and are detailed in the corresponding program sections. In addition, IRIS will pursue partnerships with other US and international organizations and agencies to provide IRIS members with the opportunity to become involved in activities of broad societal impact in developing countries.

Coordination with IS (through WBS 3.1.8.4)

In coordination with IDS, Instrumentation Services will work to provide network managers and operators with training in best practices for designing, acquiring, implementing, operating, and sustaining seismic networks with the goal of facilitating the generation of high-quality seismological data. IDS will coordinate the organization of these training opportunities with foreign partners, and will seek supplemental support from non-US government entities.

Coordination with DS (through WBS 3.2.7)

IDS will work with Data Services on activities such as metadata workshops for network managers and operators from developing countries, the REED program in support of network telemetry, and enhancements to the widely used and freely available SeisComp-3 network management software. IDS will support the coordination of these activities with foreign partners, and will pursue US and foreign supplementary funding sources.

Coordination with EPO (through WBS 3.3.5)

IDS will work with EPO to establish partnerships in developing countries to develop culturally adapted educational materials in seismology and earthquake-related hazards. In addition, IDS will assist in coordinating the contributions of EPO in support of international capacity-building efforts led by IS and DS, building on successful IDS Advanced Studies Institutes held in 2011 and 2012. This support will include development of an online data processing library of instructional software, sample data sets, and corresponding documentation.

CONCLUSION

Because of the long-term sustained support by NSF, the next decade will see a transformation of the scientific field of seismology from a methodical, data-driven, labor-intensive, and self-standing discipline, to a field that will reveal a wealth of knowledge about Earth's structure and its intimate coexistence with its biosphere and atmosphere. The technological developments that are enabling this rapid evolution will also facilitate global-scale interdisciplinary observations through expanded international collaborations. These developments will result in an accelerated pace of discovery and in expanded opportunities to translate new knowledge into tangible societal benefits.

IRIS' commitment to facilitate seismological research encompasses multiple strategies for encouraging international partnerships and optimal stewardship of NSF funds. These include seizing opportunities to leverage IRIS resources to support the development of international cadres of partners and collaborators, and generally raise the profile of seismology, particularly in regions where scientifically interesting seismic activity represents a threat to local populations, or where the use of seismological techniques can lead to the discovery of natural resources with important social and economic impact.

Through coordination of programmatic resources, IRIS will undertake the dual opportunity and responsibility to embark in large-scale international projects and to develop and engage international partners who can lead and support the global societal impact of the science of seismology.

Summary

In this proposal we have outlined a plan for a suite of integrated seismological facilities that address pressing societal and basic science questions. To advance our understanding of the complex problems of earthquake physics and Earth structure requires long-term, dense, high-quality, and publicly accessible data. To ensure our data contribute to a broad array of scientific and societal issues, we encourage free and open access to data and seek opportunities for collaboration with other disciplines. Already IRIS-facilitated seismic data are becoming increasingly applied to related fields such as geomorphology, glaciology, atmospheric science, ocean dynamics, environmental science, hazard assessment, and volcanology.

The *Seismological Facilities for the Advancement of Geosciences and EarthScope* are being developed and implemented through a community-based governance and management structure that is designed to ensure continuous involvement, guidance, and decision-making by the scientists that the facilities serve. The IRIS Consortium provides a structure and mechanism for the US research community to identify, articulate, and implement the facilities required to retain the position of US seismology at the forefront of global research in Earth sciences. This proposal is the road map identified by the community to develop and sustain our resources for the coming five years and to prepare for the future. Through the activities proposed here, IRIS will pursue the goals identified in the Introduction: maintain and improve the core facilities, complete the EarthScope facility plan, educate our community and the public, and look to the future to develop the instrumentation and services required to provide scientists everywhere with a window into Earth.

This proposal builds upon past investments by NSF in instruments and facilities and continues the stewardship of these resources. A number of the activities proposed here are natural continuations of established programs that the community relies on throughout their research endeavors. The efficiency and operation of these programs will be improved through efforts such as the ongoing upgrade of the GSN, implementation of enhanced techniques to improve and track the quality of data, acquisition of specialized equipment for polar use, and integration of all instrumentation services. The completion of the TA in the eastern United States and its deployment to Alaska will provide exciting new data as part of the completion of the EarthScope facility plan. The operation of stations in Cascadia and the central and eastern United States will provide data sets critical to numerous new and evolving research questions. To ensure the continued leadership of the US research community, IRIS will explore new technologies focused on next generation instrumentation and their application in arrays and subduction zone observatories, along the way setting standards for observational systems that will benefit seismic networks throughout the world. The DMC will continue archiving a diverse collection of data and operating data management and distribution systems—providing access to the quality-controlled data and derived data products that are the lifeblood of observational seismology. Finally, we will communicate exciting and important issues to the public, students, and fellow scientists both in the United States and internationally by documenting best practices, enhancing international collaboration, and implementing new outreach at a number of educational levels.

The IRIS Consortium, and the facilities it operates, are driven forward by a robust and active research community that continues to evolve in anticipation of, and in response to, new science questions, such as those as articulated in science planning documents from the National Academy of Sciences, federal agencies, and the community itself. The science opportunities that lay ahead provide the basis for an integrative facility that spans many activities. This proposal anticipates and encourages the participation of students, young researchers, and faculty as well as the established scientific community in defining this facility. Through the facilities it operates, IRIS provides data and instruments that are an essential component of the research infrastructure for seismology, but the Consortium is also an avenue for engagement of the community in the important tasks of governance and direction of their science resources over the coming years. Thus, NSF's support for the Consortium in managing its multi-user facilities also helps develop the next generation of scientific leaders.

Budget Plan

BUDGET SUMMARY

This Budget Plan provides an overview of the primary budget components and funding structure for the activities presented in the Project Description. The Budget Summary presents various representations of the total five-year budget in tabular and graphical form. Brief explanations of the budget components and funding mechanisms for each of the programmatic components by Work Breakdown Structure (WBS) and some general information on cost assumptions used in developing the budget follow. Additional details and explanations are found in the NSF 1030 budget forms (with the annual and cumulative budgets for the full project and subawards) in Volume 2, Section II, and in the WBS Dictionary submitted as a supplementary document in Volume 2, Section III. Although NSF requested that budget details be provided at WBS level 3, information is provided here at WBS level 4 for Instrumentation Services (to provide more detail on these programmatic areas) and at level 3 for all other WBS elements.

Table BP-1 presents the full annual and five-year cumulative budgets by WBS element. The five-year funding request follows the budget guidance provided by NSF for the combined IRIS core and USArray activities ($146,640,000), plus funds for Polar Support Services ($5,724,248), which follows guidance provided by the Office of Polar Programs. The total funding requested for five years is $152,382,248. The funds proposed will be expended starting October 1, 2013 (start of FY14) and ending September 30, 2018 (end of FY18). The years in the text and tables of this proposal refer to the fiscal year in which the funds are planned for expenditure.

Figure BP-1 shows the total five-year budget, as percentage and total funding request, for the primary WBS elements. Figure BP-2 shows the same five-year budget broken down into standard NSF 1030 budget categories.

Table BP-1. Budget – Seismological Facilities for the Advancement of Geosciences and EarthScope – 2013–2018

WBS	Element	FY14 Year 1	FY15 Year 2	FY16 Year 3	FY17 Year 4	FY18 Year 5	5-Yr Totals
3.0	SEISMOLOGICAL FACILITIES FOR THE ADVANCEMENT OF GEOSCIENCES AND EARTHSCOPE	28,697,779	29,562,743	30,447,391	31,363,429	32,310,907	152,382,248
3.1	INSTRUMENTATION SERVICES	20,303,812	21,109,770	21,439,117	22,570,656	23,031,722	108,455,076
3.1.1	IS MANAGEMENT	1,609,086	1,646,358	1,684,559	1,723,714	1,809,645	8,473,362
3.1.2	IS GOVERNANCE	10,210	10,210	10,210	10,210	10,210	51,050
3.1.3	PORTABLE SEISMOLOGY	4,325,001	4,460,001	4,560,000	4,510,000	4,510,000	22,365,002
3.1.3.1	Management	67,000	67,000	67,000	67,000	67,000	335,000
3.1.3.2	Governance	27,500	27,500	27,500	27,500	27,500	137,500
3.1.3.3	Operations	4,230,501	4,365,501	4,465,500	4,415,500	4,415,500	21,892,502
3.1.4	GLOBAL SEISMOGRAPHIC NETWORK (GSN)	3,052,639	2,928,204	3,231,213	3,233,432	3,038,872	15,484,360
3.1.4.1	Management	69,750	69,750	69,750	69,750	69,750	348,750
3.1.4.2	Governance	32,500	32,500	32,500	32,500	32,500	162,500
3.1.4.3	GSN Operations	2,650,389	2,675,954	3,028,963	3,081,182	2,886,622	14,323,110
3.1.4.4	Geophysical Observatories	275,000	125,000	75,000	25,000	25,000	525,000
3.1.4.5	GSN Coverage	25,000	25,000	25,000	25,000	25,000	125,000
3.1.5	POLAR SUPPORT SERVICES	1,077,779	1,112,743	1,147,391	1,183,429	1,220,907	5,742,249
3.1.5.1	Management	91,475	93,121	93,121	93,121	93,121	463,959
3.1.5.2	Governance	5,500	5,500	5,500	5,500	5,500	27,500
3.1.5.3	Polar Operations	980,804	1,014,122	1,048,770	1,084,808	1,122,286	5,250,790

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Table BP-1. Budget – Seismological Facilities for the Advancement of Geosciences and EarthScope – 2013–2018, continued…

		FY14 Year 1	FY15 Year 2	FY16 Year 3	FY17 Year 4	FY18 Year 5	5-Yr Totals
3.1.6	TRANSPORTABLE ARRAY	8,775,084	9,640,513	8,893,721	9,950,907	10,115,651	47,375,875
3.1.6.1	Management	351,660	356,084	371,856	369,159	380,363	1,829,122
3.1.6.2	Equipment	2,295,894	3,367,991	2,892,689	2,925,821	2,443,787	13,926,182
3.1.6.3	Array Operations	3,177,292	2,824,956	3,063,231	3,995,114	5,155,661	18,216,254
3.1.6.4	Station Deployment	2,700,708	2,839,612	2,565,945	2,660,813	2,135,840	12,902,918
3.1.6.5	Cascadia	249,530	251,870	0	0	0	501,400
3.1.7	MAGNETOTELLURICS	698,957	716,027	733,521	751,451	769,831	3,669,787
3.1.7.1	Management	68,063	68,790	71,896	74,241	77,156	360,146
3.1.7.2	Permanent MT	128,182	134,665	139,095	141,829	145,410	689,181
3.1.7.3	Transportable MT	353,788	365,942	367,681	377,750	382,481	1,847,642
3.1.7.4	Flexible MT	36,506	37,350	40,953	42,810	44,456	202,075
3.1.7.5	Data	112,418	109,280	113,896	114,821	120,328	570,743
3.1.8	IS COORDINATED ACTIVITIES	755,056	595,714	1,178,502	1,207,513	1,556,606	5,293,391
3.1.8.1	Large N Prototype System	300,556	531,714	961,278	1,002,034	1,323,863	4,119,445
3.1.8.2	Global Array of Broadband Arrays (GABBA)	348,500	64,000	217,224	118,479	118,743	866,946
3.1.8.3	Subduction Zone Observatory (SZO)	106,000	0	0	0	0	106,000
3.1.8.4	Training and Best Practices	0	0	0	87,000	114,000	201,000
3.2	DATA SERVICES	5,719,880	5,853,062	6,142,946	5,998,686	6,237,131	29,951,705
3.2.1	Management	1,125,336	1,152,719	1,180,788	1,209,554	1,239,045	5,907,442
3.2.2	Governance	25,000	25,000	25,000	25,000	25,000	125,000
3.2.3	Data Management and DMC Operations	1,468,066	1,490,424	1,663,342	1,536,829	1,560,904	7,719,565
3.2.4	Information Technology	773,605	797,236	816,980	837,219	857,960	4,083,000
3.2.5	Products and Services	982,449	1,062,133	1,088,328	1,115,173	1,142,686	5,390,769
3.2.6	Quality Assurance Systems	1,156,924	1,137,050	1,165,008	1,193,661	1,223,036	5,875,679
3.2.7	External Data Coordination	188,500	188,500	203,500	81,250	188,500	850,250
3.3	EDUCATION AND PUBLIC OUTREACH	1,837,877	1,915,409	1,990,953	2,079,085	2,127,547	9,950,871
3.3.1	Management	357,068	360,095	368,154	377,389	385,395	1,848,101
3.3.2	Governance	31,000	31,000	31,331	31,331	31,500	156,162
3.3.3	Education & Professional Development	419,788	468,099	503,009	524,588	542,356	2,457,840
3.3.4	Web, Mobile Delivery, & Public Displays	685,596	706,467	729,486	753,545	773,021	3,648,115
3.3.5	Outreach	344,425	349,748	358,973	392,232	395,275	1,840,653
3.4	COMMUNITY ACTIVITIES	385,741	224,834	405,267	236,217	425,789	1,677,848
3.4.1	Community Workshops	230,391	65,599	242,053	68,922	254,310	861,275
3.4.2	Community Publications	155,350	159,235	163,214	167,295	171,479	816,573
3.5	INTERNATIONAL DEVELOPMENT SEISMOLOGY	375,469	384,668	394,108	403,785	413,718	1,971,748
	MANAGEMENT FEES	75,000	75,000	75,000	75,000	75,000	375,000

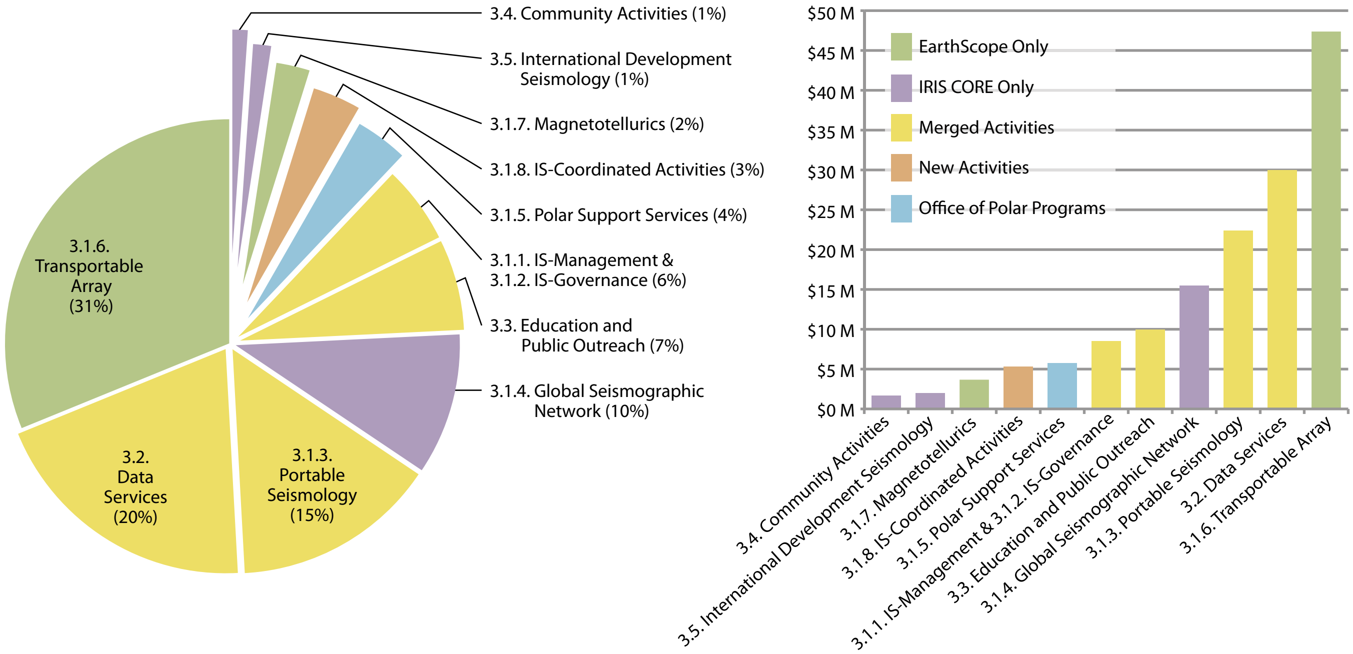

Figure BP-1. Budget breakdown by primary WBS element in % budget total (left panel) and total funding request (right panel). Colors denote the differences in funding origins prior to this proposal (EarthScope only, IRIS CORE only, Merged activities, New activities, and Office of Polar Programs support; see color key in right panel). This presentation demonstrates how the proposed budget, per NSF's request, leverages efficiencies in management, while both preserving traditional IRIS activities and enabling a robust continuation and evolution of USArray activities.

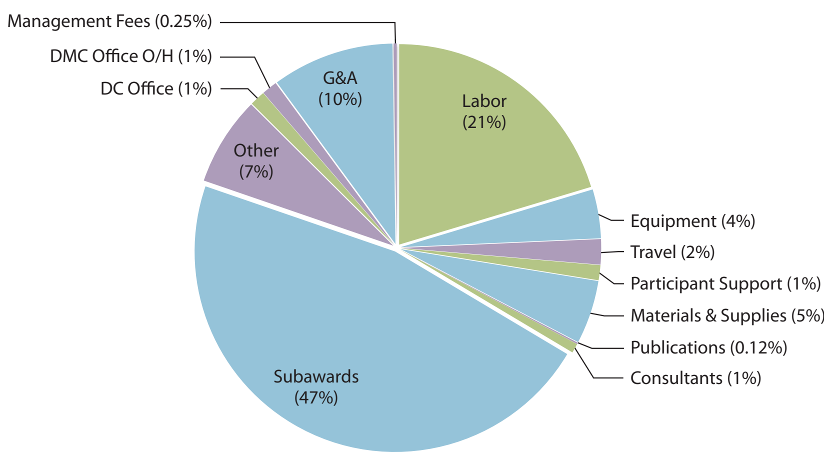

Figure BP-2. Budget breakdown by standard NSF Form 1030 categories. Further breakdown for the 2 major subawards to NMT and UCSD is provided in Figures BP-5 and BP-6. "Other" includes miscellaneous direct cost items such as meeting booths, rental, shipping, data communications, software licenses etc.

MERGED FACILITIES

This proposal represents a merging of support previously provided to IRIS for core program activities (Global Seismographic Network, Data Management System, PASSCAL, Education and Public Outreach, Community Activities, and International Development Seismology) from the NSF Division of Earth Sciences (EAR) Instrumentation and Facilities (I&F) program and the support provided for EarthScope (Transportable Array, Flexible Array, Magnetotellurics, USArray Data Services, and E&O Siting Outreach) from the EAR EarthScope program. As described in Section 3.1, all of the instrumentation programs are now managed under Instrumentation Services and, as described in Section 3.1.3, the PASSCAL and USArray Flexible Array program elements are now merged under Portable Seismology. In Figure BP-1, similar colors have been used to identify those WBS elements that were previously funded only under the I&F core Cooperative Agreement (purple: Global Seismographic Network, Community Activities, and International Development Seismology); those that were funded only under EarthScope (green: Transportable Array and Magnetotellurics); those that represent a merging of activities previously funded under both awards (yellow: Data Services, Education and Public Outreach, Instrumentation Services Management, and Portable Seismology); and those activities that are new (peach: Instrumentation Services, Coordinated Activities). Table BP-2 shows this breakdown in five-year budget totals and percentage. Almost half (46%) of the budget is for merged activities, reflecting the way in which most of the EarthScope/USArray activities were built from the start as fully integrated with the original IRIS core programs. It also points to opportunities, enhanced by the new IRIS management structure, for increased synergies in the future. While the exciting and challenging deployment of the Transportable Array to Alaska (along with the continuing operation of Transportable Array stations remaining in Cascadia and the eastern United States) is the largest individual component of the budget (31%), this presentation places it in context with the rest of a well-balanced portfolio. This budget presentation also emphasizes that a relatively small part of the total budget (3%) is being invested in important new initiatives.

Table BP-2.

	Budget	% of Budget	Category Subtotal	% of Budget
Core Only			$19,133,956	13%
GSN	$15,484,360	10%		
Community	$1,677,848	1%		
IDS	$1,971,748	1%		
EarthScope Only			$51,045,662	33%
TA	$47,375,875	31%		
MT	$3,669,787	2%		
Merged			$70,791,990	46%
Data Services	$29,951,705	20%		
ISM	$8,524,412	6%		
Portable	$22,365,002	15%		
EPO	$9,950,871	7%		
New			$5,293,391	3%
IS Coord. Act.	$5,293,391	3%		
OPP			$5,742,249	4%
Polar	$5,742,249	4%		
Total Budget*	$152,007,248	99.8%		

Excluding Management Fees

CROSS WBS CATEGORIES

At the request of NSF, we present in Figure BP-3 and Table BP-3 the allocation of budget resources into categories that cross multiple WBS elements (management, governance, instrumentation, and data). All WBS elements include expenses related to management and governance and most elements include components related to data and instrumentation. These categories are divided in the following manner:

- ***Management and Governance*** includes those WBS elements identified as such.
- ***Instrumentation*** includes all of *Instrumentation Services* (WBS 3.1) less the governance and management elements and the data element from Magnetotellurics (WBS 3.1.7.5).
- ***Data*** includes all of Data Services (WBS 3.2) except governance and management, plus the data element for MT.
- ***Other*** includes all remaining budget elements (primarily non-management activities under Education and Public Outreach and Community Activities).

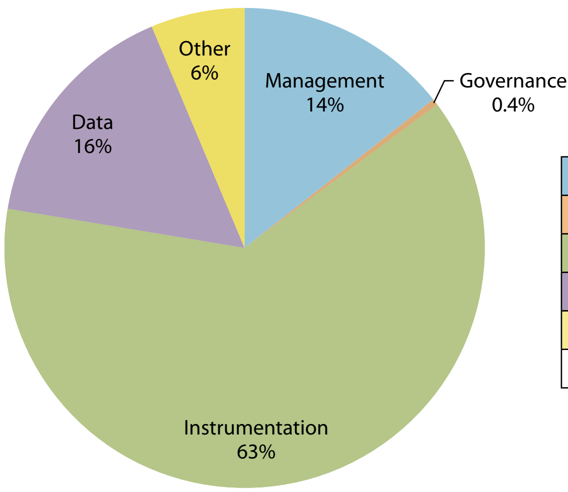

Figure BP-3. Budget breakdown showing budget components that cross Work Breakdown Structure elements as requested by NSF. Table BP-3 provides the dollar amounts corresponding to this distribution.

Table BP- 3.

Management	$21,912,630	14.4%
Governance	$659,712	0.4%
Instrumentation	$95,695,444	62.8%
Data	$24,490,006	16.1%
Other	$9,624,456	6.3%
Total Budget	$152,382,248	100.0%

PROGRAM ELEMENTS – MANAGEMENT, STAFFING, AND SUBAWARDS

In the remainder of this budget outline, we summarize the organizational structure related to management, staffing, and subawards for each WBS element and provide additional breakdown of the structure and costing of tasks within the two cross-programmatic subawards to New Mexico Tech and the University of California, San Diego. This information is intended to supplement the budget details that are found in the budget section of Volume 2 and in the Work Breakdown Structure Dictionary.

The IRIS management diagram in the Governance and Management section earlier in this proposal shows the differences in organizational structure for the different service areas. For example, IRIS employees at IRIS-managed facilities carry out most of the Data Services and EPO activities, with minor subawards and consultant agreements for specialized tasks. In contrast, the activities under Portable Seismology, GSN, and TA are largely carried out through subawards. These differences in organizational structure between programs can be seen in Figure BP-4 as the relative balance between expenses for subawards and labor (IRIS salaries). In all cases, IRIS Program Managers oversee programmatic activities, whether carried out through subawards or by IRIS staff, with advice from their respective governance committees.

While the IRIS distributed management structure is not a traditional, hierarchical organizational structure, each IRIS programmatic area has strategically evolved to leverage the diverse contributions and specialized expertise that exist within IRIS and at partner organizations. The evolution of the IRIS facility and its management structure has demonstrated distinct advantages in merging talents and intellectual resources at each host institution. Further, this structure pays unique dividends in community engagement and outreach to young faculty, scientists, and students.

3.1.1-2. Instrumentation Services Management & Governance

Under the new combined Instrumentation Services management structure, TA and MT management are integrated into the existing IS component, which currently comprises PASSCAL, GSN, Portable Seismology, and Polar Support Services management. The Instrumentation Services Management budget (WBS 3.1.1) includes the salary support for the Director of Instrumentation Services and the salaries of the program managers for each of the IS components, plus staff associates.

3.1.3. Portable Seismology

Portable Seismology combines the current PASSCAL and USArray Flexible Array activities supported under separate Cooperative Agreements from the NSF Instrumentation and Facilities and EarthScope programs. The core of the Portable Seismology operations is through the Portable Seismology task included in the subaward to New Mexico Tech for operation of the PASSCAL Instrument Center (PIC) and primarily covers staff support. A smaller subaward to UTEP provides support of the shared Texan instrument facility. All permanent equipment for PS and most field supplies and travel

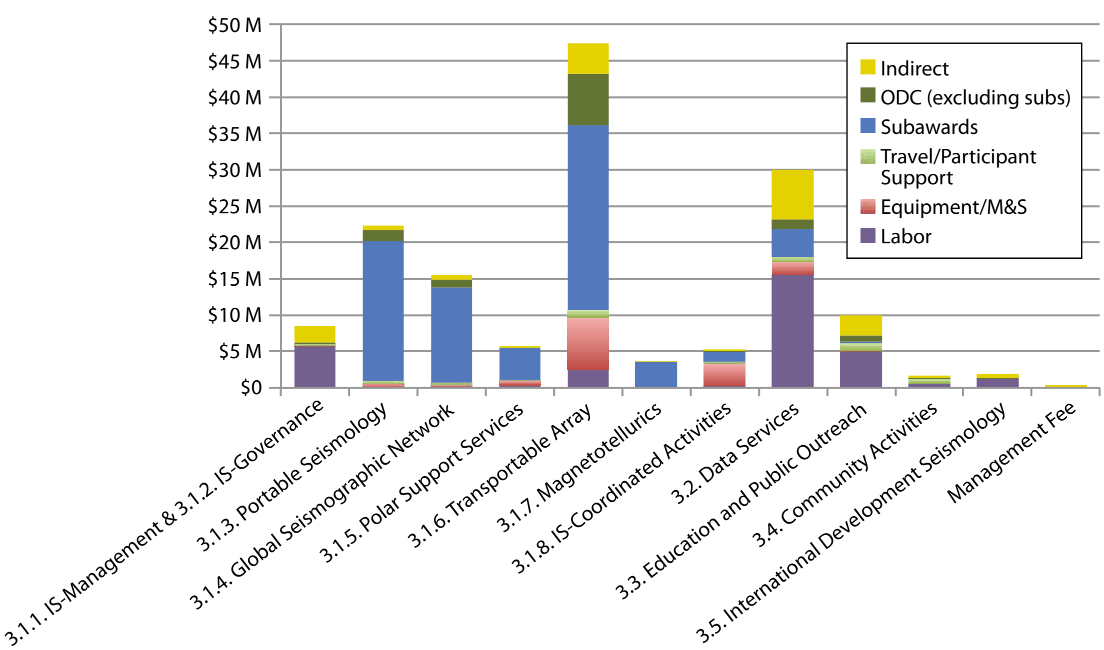

Figure BP-4. Budget breakdown showing distribution of cumulative five-year funds proposed for each NSF Form 1030 category for each WBS element.

are charged directly to IRIS, rather than through the New Mexico Tech subaward. IS Management includes salary for the Portable Seismology Program Manager.

3.1.4. Global Seismographic Network

The Global Seismographic Network task in the subaward to UC San Diego covers personnel and operational costs for station operations of the 41 stations in the IDA component of the GSN. IRIS directly pays for major equipment items and some of the communications costs. IS Management includes salary for the GSN Program Manager.

Operation of the GSN is carried out in partnership with the USGS. A Memorandum of Understanding between the NSF and the USGS establishes the general framework for interagency collaboration in research in the Earth sciences, and an Annex on the GSN between NSF, USGS, and IRIS describes the arrangements for GSN support and operation. Until recently, all permanent equipment for both IDA and USGS stations was provided through IRIS/NSF. Recent augmentation of the USGS GSN budget and a special augmentation with ARRA funds appropriated to USGS in 2009 have allowed USGS to assume a larger role for the acquisition of equipment for their stations. Full funding for the GSN thus includes an additional approximately $4 M per year spent by the USGS to operate their component of the GSN.

3.1.5. Polar Support Services

This proposal includes a request (to be funded by NSF's Office of Polar Programs) to utilize the staff and facilities of the Polar Support Services group at the PIC and to provide specialized cold-hardened instrumentation to support projects in both polar regions. The staffing support is funded under the Polar Support Services task in the New Mexico Tech subaward. Permanent equipment items and supplies are purchased directly by IRIS. It is anticipated that supplemental funding for equipment will be provided by OPP on an annual basis for any special instrumentation requirement arising from new PI projects. Management oversight for PSS will be coordinated through IS Management. The proposal includes partial support for a Polar Support Services Manager and we intend to seek funds through OPP or other sources to increase this level of support to hire a dedicated FTE for this position.

3.1.6. Transportable Array

The Transportable Array is managed by a small team of five IRIS employees, led by the TA Manager, which is responsible for oversight of all procurement, permitting, siting, installation, operation, and data collection activities. Staging and preparation of equipment (Array Operations Facility) and some permitting and field coordination (TA Coordinating Office) are performed at the PASSCAL Instrument Center under the TA task in the subaward to New Mexico Tech. Installation is carried out by an engineering team under a subaward to Honeywell Technical Services Incorporated. Data collection, network monitoring, and metadata management are performed at the Array Network Facility (the ANF task in the UCSD subaward). All equipment is purchased directly by IRIS. IS Management includes salary for the TA Manager.

3.1.7. Magnetotellurics

All MT activities are funded through a subaward to Oregon State University. Oversight and coordination are provided through IS Management by the Director of Instrumentation Services.

3.1.8. Instrumentation Services Coordinated Activities

The new technology developments proposed as IS Coordinated Activities will integrate activities across all IS programmatic elements. The subaward to New Mexico Tech includes tasking in this area for both participation in the development program and support during field testing of the pilot arrays.

3.2. Data Services

Most Data Services activities are carried out by IRIS staff at the Data Management Center in Seattle. The subaward to UCSD includes a Data Collection Center task, managed through Data Services, for preparation, quality control and metadata management of data from the IRIS/IDA/GSN stations.

3.3. Education and Public Outreach

The Education and Public Outreach staff, located at IRIS Headquarters in Washington, DC, perform most of the EPO activities, using highly leveraged interactions with Consortium members and collaborating organizations. A number of small subawards are managed by EPO, primarily related to the development of educational materials.

3.4. Community Activities

Staff at IRIS Headquarters in Washington, DC, are responsible for organization and logistic arrangements for workshops and meetings and the production of IRIS publications.

3.5. International Development Seismology

The funding request for IDS is primarily for IRIS FTE positions to coordinate international activities, through cross-programmatic activities across all service areas within IRIS, through exploration of interagency and international opportunities for support of seismology, and through interactions with Consortium members involved in international research projects.

MAJOR CROSS-PROGRAMMATIC SUBAWARDS

As Figure BP-2 shows, a significant part of the proposed budget is to support multiple subawards. Two of the largest subawards, to UCSD and New Mexico Tech, involve activities that span tasks associated with multiple WBS elements. Under this merged proposal, all of the activities at these institutions, which had previously been carried out under individual programmatic subawards, are being funded under a single subaward to each institution. This is not only to coordinate management across activities and tasks, but also because of NSF limitations on the issuing of multiple subawards to a single institution under one Cooperative Agreement.

The subaward documents from NMT and UCSD included in the budget section in Volume 2 show the annual and cumulative budgets for all tasks. To provide additional information on the costs related to individual tasks under each subaward, Figure BP-5 and Table BP-4 show the cumulative budgets for each task for under the NMT subaward and Figure BP-5 and Table BP-5 show a similar breakdown for UCSD. Further details on the activities and costing for each WBS are found in the WBS Dictionary.

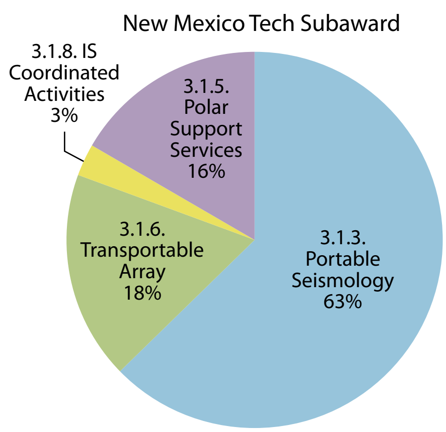

Figure BP-5. Cumulative activities across WBS elements for the New Mexico Tech subaward. This distribution of effort for several programs reflects the diversity of efforts provided by the subawardee as IRIS and EarthScope have evolved and matured.

Table BP- 4.

WBS	NMT Task Description	NMT Budget	% of Budget
3.1.3. Portable Seismology	PIC - Operations	$17,015,002	62.69%
3.1.6. Transportable Array	AOF/TACO	$4,863,003	17.92%
3.1.8. IS Coordinated Activities	New Technologies	$750,002	2.76%
3.1.5. Polar Support Services	PIC - Polar	$4,511,415	16.62%
NMT 5-Year Total		$27,139,422	100.00%

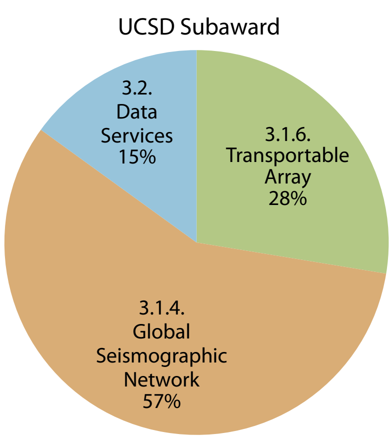

Figure BP-6. Cumulative activities across WBS elements for the UC San Diego subaward. This distribution of effort for several programs reflects the diversity of efforts provided by the subawardee as IRIS and EarthScope have evolved and matured.

Table BP- 5.

WBS	UCSD Task Description	UCSD Budget	% of Budget
3.1.6. Transportable Array	ANF/Metadata	$6,059,863	27.59%
3.1.4. Global Seismographic Network	IRIS/IDA GSN Operations	$12,604,360	57.38%
3.2 Data Services	IRIS/IDA Data Collection Center	$3,302,227	15.03%
UCSD Five-Year Total		$21,966,450	100.00%

GENERAL COST ASSUMPTIONS

A number of general cost assumptions that guided the preparation of the budget are summarized below.

Labor Costs

A list of all IRIS personnel supported through this award and senior personnel identified on subawards is included at the end of the Work Breakdown Structure Dictionary. Personnel-related costs for each program include salaries, fringe, and overhead. For the purposes of estimating salary costs in this proposal, IRIS staff salaries are increased 2.5% annually. Salaries expense reflects the portion of total annual compensation that is projected to be charged as direct salaries expense to the award. The portion of total annual compensation associated with paid time off is allocated to a fringe benefits pool. Fringe benefits expenses have been budgeted at 56% of the direct salaries expense (i.e. total salary less compensation for paid time off). In addition to the portion of salary paid for holidays and leave, fringe benefits include payroll taxes, workers compensation, health and life insurances, short- and long-term disability insurance, retirement plan employer contributions, parking, commuting, and educational benefits.

Indirect Expenses

IRIS' indirect rate agreement is negotiated annually with the Cost Analysis and Audit Resolution Branch of the NSF Division of Institution and Award Support. The rates used in this proposal are based on the projected maximum provisional rates submitted for the budget period July 1, 2012–June 30, 2013. IRIS' indirect rates are contingent upon the overall level of funding and program activities in any given budget year. The applicability of the current indirect rates is based on the projection that there will be no significant change to IRIS' cost structure and general level of activity over the next five years. Indirect rates will be updated annually during the award period based on actual levels of funding.

IRIS allocates indirect expenses through three indirect cost pools: two office overhead pools and an IRIS-wide general & administrative (G&A) expenses pool.

Each office overhead pool includes costs associated with the specific office location, such as the office manager labor, rent, office supplies, office equipment leases, telephone, and Internet, that are shared by all IRIS staff at that location. Overhead rates are established separately for the IRIS Headquarters in Washington, DC (37%), and the IRIS Data Management Center in Seattle, WA (20%). Office overhead is applied using as a base the total salaries expense of employees who work at each location.

G&A expenses include all other allowable costs that benefit all programs and cannot be easily allocated directly to a specific award. These items include the senior executive, administrative, and accounting personnel salaries, human resources administrative expenses, corporate insurances, bank, auditing and legal fees, as well as Board governance and travel. The G&A rate is applied using a modified total cost base (total costs less equipment, participant support costs, and subcontract costs exceeding $25,000 per contract per year). The current proposed maximum provisional IRIS G&A rate is 25%.

IRIS management fees are budgeted at $75,000 per year, which is the total of the fees previously awarded under the current EarthScope award ($25K) plus earlier I&F IRIS core awards ($50K). No increase or escalation of management fees is requested.

Committee Expenses

Expenses for governance include reimbursed travel for committee members and other meeting expenses for standing committees, advisory committees and working groups. As discussed in the earlier section on Governance and Management, the Board is now carrying out an assessment of IRIS governance and considering changes intended to streamline the interface among the Board, programs, and management. In the proposal budget, each of the program areas retains their current advisory structure and associated expenses. As a new governance structure is implemented, the way in which the funds for governance are used may change. The continued engagement of the community in governance and management is essential. An example of the evolution of governance includes a greater emphasis on technology-assisted "virtual" meetings, which have already been used frequently with significant success. Further, committee structure may evolve to make more use of cross-programmatic committee engagement. As shown in Figure BP-3 and Table BP-3, the funds allocated to governance represent less than 0.5% of the total budget and this is considered to be a reasonable and important investment for the future health of the consortium and its facilities.

Acronym Glossary

AGAP .... Antarctica's Gamburtsev Province – multidisciplinary program in Antarctica
AGU............. American Geophysical Union
ANF .... Array Network Facility – a USArray facility at UCSD
AOF .... Array Operations Facility – a USArray facility at NMT
APOS .... Autonomous Polar Observing Systems
ARRA .... American Recovery and Reinvestment Act
ASL .... Albuquerque Seismological Laboratory – USGS facility
CEUSN .... Central and Eastern US Network – proposed enhancement to seismic networks
CIDER.......... Cyber-Infrastructure Digital Education and Research
CIG .... Computational Infrastructure for Geophysics – NSF-funded program
COTS............ Commercial off the shelf
CTBTO .... Comprehensive Nuclear Test Ban Treaty Organization
DAS .... Data Acquisition System
DCC .... Data Collection Center
DMC .... Data Management Center
DMS............. Data Management System, a program within Data Services
DMSSC......... Data Management System Standing Committee
DoE .... Department of Energy
DS .... Data Services, an IRIS directorate
EAR .... NSF's Division of Earth Sciences
EGU .... European Geosciences Commission
EMWoG........ Electromagnetic Working Group – USArray group to advise MT program
EPO .... Education and Public Outreach
ESNO .... EarthScope National Office
ESC .... European Seismological Commission
ESSC............. EarthScope Science Steering Committee
ETS .... Episodic tremor and slip
FA................ Flexible Array - component of USArray
FDSN .... International Federation of Digital Seismograph Networks
FTE .... Full-time equivalent
GABBA .... Global Array of Broadband Arrays – as described in this proposal
GAMSEIS ...... Gamburtsev Antarctic Mountains Seismic Experiment
GEMPA......... Global Earthquake Monitoring, Processing, Analysis – German software development
GEOFON ...... Global seismology program operated by GFZ (GeoForschungsZentrum) Potsdam, Germany
GEOSCOPE ... French global network of broad band seismic stations
GLISN .... Greenland Ice Sheet monitoring Network – MRI funded
GPS.............. Global Positioning System
GRACE .... Gravity Recovery and Climate Experiment – NASA satellite program
GSN .... Global Seismographic Network
GSNSC.......... GSN Standing Committee

HTSI .... Honeywell Technical Services Incorporated – installation contractor for TA
IASPEI.......... International Association of Seismology and Physics of the Earth's Interior
IDA............. International Deployment of Accelerometers – UCSD operated component of the GSN
IDS .... International Development Seismology
IRIS............. Incorporated Research Institutions for Seismology
IS................ Instrumentation Services, an IRIS directorate
ISAES .... International Symposium on Antarctic Earth Sciences
IUGG............ International Union of Geodesy and Geophysics
MCR............ Midcontinent Rift
MEMS .... Micro-Electro-Mechanical System – possibly technology for seismometer development
MREFC......... Major Research Equipment and Facilities Construction – an NSF program
MRI .... Major Research Instrumentation – program at NSF
MT.............. Magnetotelluric
MUSTANG.... Modular Utility for STAtistical kNowledge Gathering
NASA .... National Aeronautics and Space Administration
NIMS .... Narod Intelligent Magnetotelluric System
NMT .... New Mexico Tech
NGS .... Next generation field system – for GSN stations
N-NGS.......... Next-next generation seismometer – for GSN stations
NOAA........... National Oceanic and Atmospheric Administration
NRC .... National Research Council
NSF............. National Science Foundation
OBS .... Ocean bottom seismometer
OBSIP .... Ocean Bottom Seismic Instrument Pool – supported by NSF Division of Ocean Sciences
OCE .... NSF's Division of Ocean Sciences
O&M........... Operation and maintenance
OPP .... NSF's Office of Polar Programs
OSU .... Oregon State University
PASC .... PASSCAL Standing Committee
PASSCAL....... Program for Array Seismic Studies of the Continental Lithosphere
PBO .... Plate Boundary Observatory – UNAVCO operated geodetic component of EarthScope
PI .... Principal Investigator
PIC .... PASSCAL Instrument Center – at New Mexico Tech
PFP............. Polar facility plan – Report from NSF funded workshop in 2012
PM.............. Program Manager
PNSC .... Polar Networks Science Committee – joint IRIS/UNAVCO committee
POLENET ..... Polar Earth Observing Network
- ANET...... POLENET - Antarctic Network
PS............... Portable Seismology
PSS .... Polar Support Services – IRIS polar group
QAS .... Quality assurance system
QA/QC.......... Quality Assurance/Quality Control
QCN............ Quake Catcher Network

RAPID .... Rapid Response Research program at the National Science Foundation
REED .... Regional Exchange of Earthquake Data – IRIS Data Services program in Central Asia
RefNet......... Reference Network – reference for USArray, mainly USGS Advanced National Seismic System Backbone Network
SAFOD .... San Andreas Fault Observatory at Depth – part of EarthScope facility
SCAR............ Scientific Committee on Antarctic Research
SCEC .... Southern California Earthquake Center – NSF/USGS-funded program at the University of Southern California
SEED............ Standard for the Exchange of Earthquake Data
SOH .... State-of-health
SPUD........... Searchable Product Depository – the DMC's primary data product management system
SZO.............. Subduction Zone Observatory – as described in this proposal
TA................ USArray Transportable Array
UCSD-IDA .... University of California, San Diego, Project IDA - IRIS-supported component of GSN
USAAC .... USArray Advisory Committee
USGS............ US Geological Survey
UTEP .... University of Texas, El Paso
VSAT............ Very Small Aperture Terminal
WBS............. Work Breakdown Structure

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