Enabling Discoveries in Multiscale Earth System Dynamics

SEISMOLOGICAL AND RELATED CAPABILITIES FOR THE NATIONAL GEOPHYSICAL OBSERVATORY FOR GEOSCIENCE (NGEO)

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Volume 1. Project Description and Scientific Justification

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PROJECT DESCRIPTION

1. Introduction

The Incorporated Research Institutions for Seismology (IRIS) and its partners at the New Mexico Institute of Mining and Technology (NMT), University of California, San Diego (UCSD), and University of Wyoming (UWyo) are pleased to submit this proposal in response to NSF Program Solicitation 16-546, "Management and Operation of the National Geophysical Observatory for Geoscience (NGEO)." IRIS is a consortium of 125 U.S. academic institutions, 22 Educational Affiliates, and 127 Foreign Affiliates dedicated to the operation of facilities for the acquisition, management, and distribution of seismological and other geophysical data in support of research and education in the geosciences. This proposal has been prepared in coordination with UNAVCO, our long-time partner and operator of geodetic facilities for the NSF.

Overarching Vision for the NGEO Facility

We propose the National Geophysical Observatory for Geoscience (NGEO) as a distributed, multi-user, national facility that will provide state-of-the-art geodetic, seismic, and related geophysical instrumentation and services to support research and education in the geosciences. Over the next decade, an integrated set of foundational and frontier facility capabilities will enable transformative advances in our understanding of Earth structure and dynamics, earthquakes and volcanic eruptions, and interactions between the solid Earth, hydrosphere, and atmosphere through the management and operation of:

- Global and regional continuously operating geodetic, seismic, and related geophysical networks
- Portable seismic, geodetic, and related geophysical instrumentation for use in principal investigator (PI)-driven and community experiments
- Data management systems for the collection, quality assurance, curation, management, and distribution of open access geophysical time-series data and data products
- Education, workforce development, and public outreach programs designed to be inclusive and enhance participation of traditionally underrepresented groups in the geosciences

We envision the NGEO as a facility "Center of Excellence" as described in the community report *Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences* (Aster and Simons, eds., 2015). As a facility Center of Excellence, the NGEO will:

- Make available state-of-the-art geodetic, seismic, and other geophysical instrumentation for a wide variety of PI-led and larger-scale community experiments
- Facilitate scientific breakthroughs by developing new facility capabilities to meet the rapidly evolving needs of cutting-edge science
- Collect, archive, and distribute geodetic, seismic, and other geophysical data in standard formats and make these data freely and openly available to all
- Employ a highly skilled, dedicated professional, technical, and administrative staff to maintain and operate the facility to the highest possible standards
- Establish and maintain a community-based governance and oversight structure to ensure the facility is responsive to community needs and is operated transparently and efficiently
- Support informal and formal education (at all levels) and enhance literacy in geoscience within the broader community
- Integrate workforce development and increase diversity throughout the activities of the NGEO facility
- Provide technical and engineering expertise in the development, evaluation, and implementation of new technologies to enhance the capabilities of existing facilities, obtain new types of data, and operate in extreme environments
- Seek partnerships, nationally and internationally, to enhance the facility capabilities available to the broader geoscience community

The NGEO will make it possible for investigators from diverse backgrounds, at different career stages, and from institutions ranging from community colleges to internationally renowned research universities to have equal access to world-class facilities to advance geoscience research and education. Managed and operated jointly by IRIS and UNAVCO, the NGEO will also enable closer integration and coordination between geodetic and seismological facilities and programs while providing new facility capabilities for other geophysical disciplines that will broaden the community of geoscientists that the NGEO facilities support.

IRIS Expertise in Operating Large Scientific Facilities

Headquartered in Washington, DC, IRIS is organized as a 501(c)(3) nonprofit corporation. IRIS has the business and financial systems needed to receive and manage federal funds through Cooperative Agreements and other awards from the NSF and other agencies and sponsors. Formed in 1984, IRIS has developed and managed seismological facilities for the NSF for over 30 years. Over this time, IRIS has established an outstanding reputation for management of large, multi-user facilities for research and education in the geosciences. IRIS also plays an important role in building and maintaining a vibrant research community in seismology and educating a scientifically and technology able workforce.

IRIS's success in facility management is built on five guiding principles: (1) setting global standards for instrumentation, data formats, and data quality; (2) making instruments widely available to researchers through national, shared-use facilities; (3) establishing a culture of open and free exchange of data; (4) integrating research and education into facility operations; and (5) utilizing a governance model that directly engages the community in carrying out and overseeing facility operations.

Many IRIS-managed facilities are operated through subawards to universities and colleges who are themselves leaders in geoscience research and education. This leverages the scientific and technical expertise of the academic community, helping ensure these facilities remain state of the art, and further engages the community in their operation. IRIS has also been quite successful in obtaining funding from other parts of the NSF, sometimes in partnership with Consortium members, to augment base facility support. For example, IRIS has obtained funds from the NSF's Major Research Instrumentation (MRI) program to acquire and develop new instrumentation and from the NSF's EarthCube program to advance cyberinfrastructure capabilities. IRIS has also been very successful in leveraging NSF support to obtain additional funding from other agencies, including the U.S. Geological Survey (USGS), Department of Energy (DOE), Department of Defense (DOD), and Department of State for instrument recapitalization and facility repairs.

As an academically based consortium, IRIS has since its inception had a "dirt-to-desktop" approach to facility operations that extends from supporting the initial collection of data in the field to delivering data and data products to a user's desktop. The feedback and coordination between the community and the facility, and between data collection, quality control, archiving, and dissemination, is extraordinarily valuable in producing the highest quality data directly relevant to high-priority research and to society. Our integrated approach to facility management allows researchers to focus on science rather than maintaining instruments or managing data, and is cost effective for the NSF, reducing administrative and management costs associated with awards to multiple organizations.

IRIS currently manages the following scientific facilities for the NSF:

- **Global Seismographic Network (GSN)** – IRIS, through a subaward to the University of California, San Diego, partners with the USGS to manage the 152-station GSN. The GSN is widely viewed as the "gold standard" for global, national, and regional seismographic networks, producing high-quality continuous data in near-real time. A dual-use network, the GSN supports basic research into global seismicity and Earth structure as well as mission-related tasks such as earthquake location and characterization, tsunami warning, and nuclear test monitoring.
- **Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL)** – Operated by New Mexico Tech under a subaward from IRIS, the PASSCAL Instrument Center is the world's largest open access, shared-use, portable broadband seismic instrumentation facility. It has supported nearly 900 PI-led experiments during the past 10 years, including passive and active source studies of Earth structure and tectonics, earthquake aftershock studies, and deployments to study regional and teleseismic events in field areas all around the world, including the Arctic and Antarctic.
- **Data Management Center (DMC)** – The IRIS DMC is the world's largest facility for the archiving, curation, and distribution of seismological and other geophysical data from permanent geophysical observatories, as well as temporary deployments of seismometers and other geophysical instrumentation. The DMC data archive has grown to more than 400 terabytes, and in 2016, IRIS expects to distribute nearly 1 petabyte (1024 Tb) of data to users in over 170 countries around the world.
- **EarthScope's USArray** – For the past 10 years, IRIS has operated EarthScope's USArray, a community experiment that includes a 400-element Transportable Array (TA) to image the geologic structure of the North American continent and a pool of portable seismic and magnetotelluric (MT) instruments available for PI-driven and community experiments. IRIS completed the 10-year deployment of the TA in the lower 48 states in October 2015 on time and under budget, occupying over 1700 stations. The TA is now being deployed in Alaska in one of the most technically and logistically challenging seismic experiments ever attempted.
- **OBSIP Management Office** – IRIS manages, in collaboration with subawardees at Lamont-Doherty Earth Observatory, Scripps Institution of Oceanography, and Woods Hole Oceanographic Institution, the NSF-funded Ocean Bottom Seismograph Instrument Pool (OBSIP) that currently includes 257 broadband and short-period ocean bottom seismometers. From 2011 to 2015, OBSIP conducted the offshore portion of the Cascadia Initiative, an onshore-offshore seismic and geodetic experiment designed to study tectonic, volcanic, and related processes associated with the Cascadia subduction zone.
- **Education and Public Outreach (EPO)** – The IRIS EPO program has brought unequaled access to seismic data and derived interpreted products to a wide range of audiences. IRIS provides information on recent global seismicity for millions of users each year, and develops and distributes curricula and data-rich teaching tools and animations on

seismology for grades 6–12 and undergraduate-level educators. IRIS operates a highly competitive summer research internship program for undergraduates, and has promoted Earth science literacy in the general public through creation of displays for museums and visitor centers, development of Web applications, and a rapidly expanding social media presence reaching millions of people annually.

Collectively, these facilities support scientific research and education across a broad spectrum of the geosciences. Papers utilizing data from IRIS-operated facilities are published in traditional Earth science and geophysical journals, and in journals focused on polar research, meteorology and atmospheric studies, ocean science, acoustics, computer science, planetary science, volcanology, and engineering, highlighting the unexpected and creative uses of the data and facilities operated by IRIS (**Table INTRO-1**). In 2014 and 2015 alone, data from IRIS-operated facilities were used in over 1000 peer-reviewed articles in 115 different journals, including *Nature*, *Science*, *Journal of Geophysical Research*, and the *Bulletin of the Seismological Society of America*. IRIS-operated facilities have also supported research that has caught the imagination of the general public. In 2011, EarthScope was recognized by *Popular Science* magazine as #1 on its list of "The Universe's 10 Most Epic Projects," while the amphibious portion of the Cascadia Initiative was identified by the White House in 2010 as one of "100 Recovery Act Projects that are Changing America."

IRIS/UNAVCO Partnership

IRIS and UNAVCO are submitting independent, but coordinated proposals to provide all of the facility capabilities outlined in the NGEO solicitation (**Figure INTRO-1**). If both proposals are successful, IRIS and UNAVCO have agreed to jointly operate the NGEO within the framework of a single, integrated management and governance model.

TABLE INTRO- 1. Total number of peer-reviewed papers in the top 10 journals published in 2015 that utilized data from IRIS-operated facilities.

JOURNAL/MAGAZINE	NUMBER OF REFERENCES IN 2015
#1 Journal of Geophysical Research	80
#2 Geophysical Journal International	80
#3 Bulletin of the Seismological Society of America	59
#4 Geophysical Research Letters	55
#5 Seismological Research Letters	46
#6 Earth and Planetary Science Letters	33
#7 Tectonophysics	19
#8 Nature	12
#9 Physics of the Earth and Planetary Interiors	4
#10 Science	3
TOTAL	391

Results of Prior NSF Support

EarthScope Facility Operation and Maintenance

EAR-0733069, $73,609,490, D. Simpson, R. Woodward, PIs, 10/1/08–9/30/13

IRIS 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 the NSF's Major Research Equipment and Facilities Construction account. This award provided support to IRIS for the operation and maintenance of the USArray 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-operated Advanced National Seismic System); a Transportable Array of 400 stations that has systematically traversed the continental United States on a 70 km grid occupying more than 1700 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 conductivity structure of the lithosphere. The data from all USArray instruments are freely and openly available through the IRIS Data Management Center. The USArray component of EarthScope was completed on time and under budget, a testimony to IRIS technical and management expertise.

Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE)

EAR-1261681, $86,003,462, R. Detrick, J. Taber, T. Ahern, R. Woodward, PIs, 10/1/2013–9/30/2018

This award supports the operation and maintenance of a wide range of facilities for research and education in seismology and the Earth sciences, including the Global Seismographic Network (GSN), the Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL), and the USArray component of EarthScope, including the Transportable Array, which has been integrated into IRIS's other Instrumentation Services. The IRIS Data Management System archives and freely distributes data from these facilities. Data from the GSN, PASSCAL, and USArray are a primary resource for national and international Earth science research and have helped sustain the U.S. position as a global leader in seismological research. Through collaborations with other government agencies, and with a variety of organizations internationally, the data obtained by these facilities 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 the NSF's investments in support of geoscience research. The broad reach of the IRIS Consortium's governance structure, and the active engagement of research scientists in guiding the management of IRIS-managed programs, continue to ensure that these facilities meet the evolving needs of the academic research community.

This partnership enables close integration and coordination between geodetic and seismological facilities and programs while providing new facility capabilities for other geophysical disciplines that will broaden the community of geoscientists that the NGEO facilities support. Together, IRIS and UNAVCO will provide the vision, leadership, and service to manage the NGEO as a vibrant, effective, multi-user, community-focused national resource.

IRIS and UNAVCO have a long history of collaboration in polar instrument and network services, data services, and education and public outreach. Notably, 15 years ago, IRIS and UNAVCO partnered to construct the $197 million EarthScope facility through the NSF's Major Research Equipment and Facilities Construction account, and have now successfully operated the EarthScope facilities for more than a decade, bringing the project in on schedule and under budget. EarthScope, the largest facility and science program ever funded by the NSF in the Earth sciences, was dauntingly complex in its technology, geographic distribution, aggressive schedule, and rigorous management processes. IRIS and UNAVCO cooperated at the management level on project control and financial and other reporting, change management, and site reviews, as well as at the technical level on technology and field operations. Today, as the EarthScope program enters its final phase, IRIS and UNAVCO are collaborating in Alaska, coordinating helicopter service operations, co-locating new Transportable Array sites at existing Plate Boundary Observatory (PBO) sites, and sharing in outreach to the Alaskan public. IRIS and UNAVCO also partner in EarthScope data management. IRIS archives seismic, magnetotelluric, pressure, and infrasound data from USArray and is the repository and primary distribution point for UNAVCO's PBO borehole seismometer and strainmeter data.

IRIS and UNAVCO, working together via a series of joint NSF-funded MRI proposals, revolutionized the technology for autonomous observing systems in Antarctica. As a result of joint IRIS/UNAVCO engineering efforts, power, packaging, communications, and deployment technologies systems were developed that could overwinter in the harsh Antarctic environment. These efforts resulted in an unprecedented increase in instrument overwinter survival. Today, the two organizations share logistics space in Antarctica's Palmer Station and cross-train their engineers to ensure they can back each other up when they are in the field supporting science experiments—whether seismological or geodetic.

IRIS and UNAVCO have also partnered on two successful EarthCube Building Block proposals (GeoWS, GeoSciCloud) and pioneered data distribution using Open Geospatial Consortium web services. IRIS and UNAVCO's education and outreach programs have jointly developed materials for wide dissemination via print, Web, and social media, shared booths and student field trips at diversity-focused professional meetings, and are now partnering, along with other institutions, on an NSF INCLUDES diversity project.

This long track record of successful collaboration in instrumentation services, data services, and education and public outreach activities provides a strong foundation for IRIS and UNAVCO to jointly manage and operate the NGEO facilities.

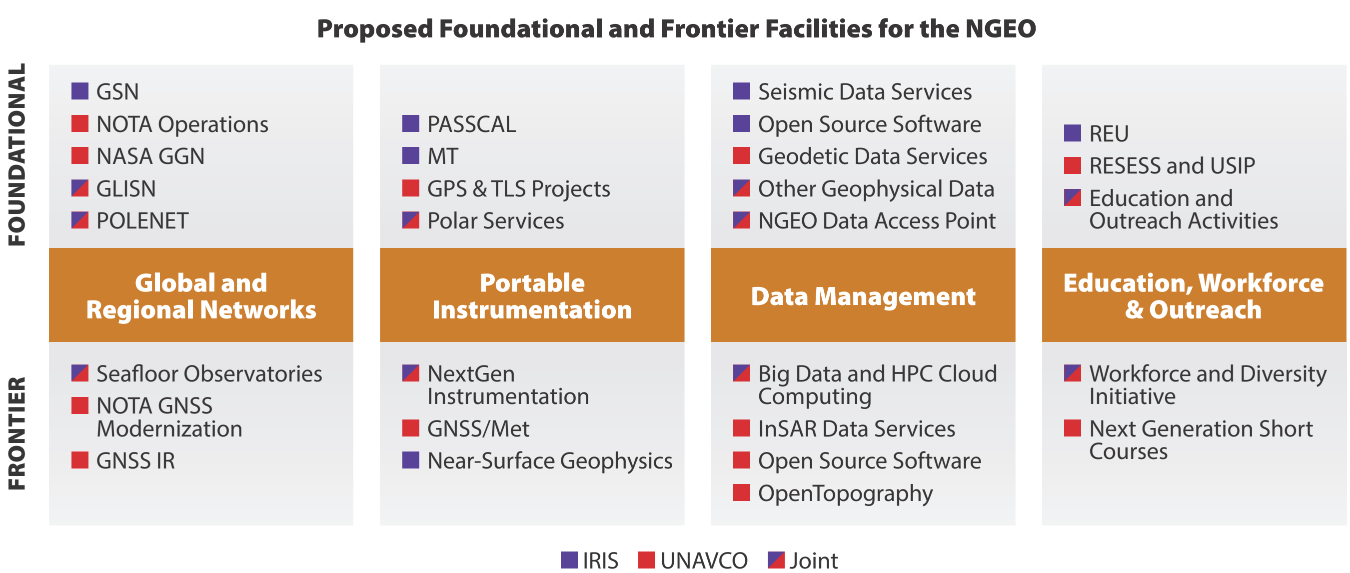

FIGURE INTRO-1. An "NGEO Roadmap" showing the foundational and frontier facility capabilities that IRIS and UNAVCO are proposing to provide separately or jointly for the NGEO. Together, the IRIS and UNAVCO proposals address all components of the NGEO solicitation while ensuring that they are operated in a coordinated, responsive, and cost-effective manner. GSN: Global Seismographic Network. NOTA: Network of the Americas. GGN: Global GPS Network. GLISN: Greenland Ice Sheet Monitoring Network. POLENET: Polar Earth Observing Network. GNSS: Global Navigation Satellite System. IR: Interferometric Reflectometry. PASSCAL: Portable Array Seismic Studies of the Continental Lithosphere. MT: Magnetotelluric Array. GPS: Global Positioning System. TLS: Terrestrial Laser Scanner. HPC: High Performance Computing. InSAR: Interferometric Synthetic Aperture Radar. REU: Research Experiences for Undergraduates – an NSF program. RESESS: Research Experiences in Solid Earth Sciences for Students – a UNAVCO diversity program. USIP: UNAVCO Student Internship Program.

2. Community Input and Overview of IRIS Facility Plans for the NGEO

A series of community-led workshops and National Academy of Sciences reports on scientific opportunities for seismology and the Earth sciences inform the facility plans presented in this proposal. These reports include the 2009 *Seismological Grand Challenges in Understanding Earth's Dynamic Systems* (Lay, 2009), the 2011 *EarthScope Science Plan: Unlocking the Secrets of the North American Continent* (Williams et al., 2010), and the 2012 report from the National Academy of Science's Board on Earth Sciences on *New Research Opportunities for Earth Sciences* (NRC, 2012). Of particular importance to this proposal is the 2015 NSF-sponsored workshop on Future Seismic and Geodetic Facility Needs in the Geosciences, including the workshop report *Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences* (Aster and Simons, eds., 2015), which we will refer to as the "Futures" Facility Workshop Report. This report synthesizes community input on future geophysical facility requirements for the next decade (and beyond) with a particular eye toward the current recompetition of the management of these facilities.

As an academic consortium, IRIS has deep roots in the academic community. In preparing this proposal, we relied heavily on input from more than 80 community members from IRIS's 125 member institutions and other organizations who serve on 11 different IRIS governance committees. Within the context of the community documents listed above, they prepared white papers in response to the NGEO solicitation describing foundational and frontier facility needs, identified how these facilities should evolve over the next 10 years to meet scientific challenges and opportunities, and developed recommendations on programmatic and budget priorities. The 2016 IRIS Workshop, attended by 235 people representing more than 80 institutions and seven countries, provided another opportunity to discuss future science directions and facility needs in the geosciences, and these discussions have informed this proposal. We also utilized questionnaires to solicit additional information on specific facility needs from the near-surface geophysics and computational geophysics communities. Our strong connections with other geophysical disciplines, and the EarthScope and GeoPRISMS, communities, further inform the facility capabilities included in this proposal. Twenty-eight community members directly participated in writing this proposal (see **sidebar**), which was approved for submission to the NSF by the IRIS Board of Directors. In every sense, this is a community-driven proposal reflecting the needs and priorities of the 125 academic institutions that are IRIS Consortium members.

Overview of IRIS Facility Plans for the NGEO

The following crosscutting themes guide our approach to facility planning, operation, and management and underlie the specific foundational and frontier facility capabilities IRIS proposes for the NGEO:

- Maintaining state-of-the-art, shared-use facilities operated by a skilled and dedicated professional staff to support cutting-edge science identified by the research community
- Incorporating new technologies into the NGEO facilities to provide enhanced capabilities to study Earth system processes
- Fostering closer integration and coordination between geodesy and seismology in instrumentation, data management, education, workforce development, and public outreach

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- Expanding NGEO facility capabilities to support a broader cross section of the geosciences community and to promote research that transcends traditional disciplinary boundaries
- Proactively engaging students and early career investigators in facility activities, and integrating workforce development and greater diversity across the NGEO
- Directly involving the geoscience community in the NGEO through community governance, workshops, meetings, publications, websites, and social media
- Developing and documenting quality standards and procedures, and implementing regular assessment of facility operations and programs, to increase the value of the NGEO to the geoscience research and education communities and the NSF
- Leveraging NSF investments in geophysical facilities through development of partnerships with other federal agencies and internationally with research and government organizations

Together, IRIS and UNAVCO are proposing an integrated set of foundational and frontier capabilities that will evolve the NGEO facilities over a 10-year period to meet the changing needs of the geoscience community (**Figure INTRO-1**).

FOUNDATIONAL FACILITY CAPABILITIES

IRIS proposes to support four foundational facilities in the NGEO to provide capabilities that are identified in the "Futures" Facility Workshop Report (Aster and Simons, eds., 2015) as "essential" to the geosciences research and educational communities. They are:

- Global Seismographic Network
- PASSCAL portable geophysical instrument pool
- Data Management System
- Innovative and broad-based programs in education, workforce development, and public outreach

Global Seismographic Network. This permanent high-quality, very broadband, global seismographic network is essential for basic research on global seismicity and Earth structure, as well as for rapid earthquake characterization, tsunami prediction and warning, and nuclear test monitoring. In this proposal, we request support to continue the NSF's successful partnership with the USGS to operate the GSN, and to continue our efforts to optimize station and network performance, maintain the high quality of GSN data, and improve the resiliency of the network. As operators of the NGEO, we will work with the seismological community to assess design goals for the GSN in light of future community needs, evaluate the availability of new technologies to enhance the operation of the GSN, and explore the feasibility of expanding the GSN into the ocean.

Portable Array Seismic Studies of the Continental Lithosphere. The PASSCAL facility maintains the world's largest open access, shared-use pool of portable broadband and short-period seismic sensors and associated equipment, a capability that is essential for both PI-driven seismic data acquisition projects and larger community experiments, including deployments in polar and glacial environments. In this proposal, we request funding to operate the PASSCAL instrument facility and support seismic field experiments in locations throughout North America and around the world. We also propose to expand the foundational capabilities of the PASSCAL facility to include wide-band and long-period magnetotelluric instrumentation. Over the course of the next 10 years, we will evolve the composition of the PASSCAL instrument pool to provide more robust, lower power, simpler-to-deploy seismic instruments better suited for the rigors of fieldwork, and to enable full waveform seismic imaging on a variety of spatial scales.

Data Management System. IRIS and UNAVCO are proposing to coordinate operation of a full-service NGEO Data Management System (DMS), collecting, curating, and distributing seismic, geodetic, and other geophysical data and data products for the geoscience community. The IRIS component of the NGEO DMS includes the IRIS DMC, the world's largest facility for the archiving, curation, and distribution of seismological and other geophysical research data and data products from permanent geophysical observatories and temporary deployments of seismometers and other geophysical instrumentation. A user will be able to enter the NGEO DMS through a single NGEO Data Access Point to discover and access all NGEO data with a single web services request. IRIS and UNAVCO will also leverage their existing infrastructure to expand the types of geophysical data in the NGEO DMS in order to enable interdisciplinary Earth system science.

Education, Workforce Development, and Public Outreach. Through its commitment to advance awareness and understanding of geophysics while inspiring Earth science careers, the NGEO facilities will engage students of all ages, especially those from traditionally underrepresented groups, as well as the general public. IRIS and UNAVCO will create formal and informal education materials for students from grade six to undergraduate and graduate levels; develop innovative summer internship programs, community college partnerships, and professional development activities; provide support for early career professionals; and engage the general public to improve geoscience literacy.

FRONTIER FACILITY CAPABILITIES

To enable transformative science, meet the changing needs of the scientific community, expand the portion of the geoscience community the NGEO facilities support, and foster greater participation of underrepresented groups in the geosciences, facility capabilities that exceed today's instrumentation and services will be needed. To meet the demands of the next decade, we propose to develop the following frontier capabilities (**Figure INTRO-1**).

Near-Surface Geophysical Facility (NSGF). This frontier initiative will establish the first national, shared-use, near-surface geophysics instrumentation facility. Located at the University of Wyoming and managed by IRIS, this facility will fill a gap in geophysical instrumentation available through existing shared-use facilities and serve the research and education needs of the critical zone science, hydrology, geomorphology, soil science, natural hazards, and engineering geophysics communities.

Next-Generation Geophysical Instrumentation. A new generation of geophysical instrumentation will provide new capabilities to study Earth processes. The IRIS portion of this joint IRIS-UNAVCO frontier initiative will support the acquisition of: (1) next-generation seismic instrumentation (~1000 three-channel nodal sensors and ~380–400 intermediate-period posthole seismographs) for full wavefield seismic imaging on a variety of spatial scales, and (2) seismic, Global Positioning System/Global Navigation Satellite System (GPS/GNSS) geodetic, and other geophysical instrumentation with real-time or near-real-time telemetry for rapid response to earthquakes, volcanic eruptions, landslides, and other geophysical events.

Seismo-Geodetic Seafloor Instrumentation. One of the most challenging frontiers in geophysics is the capability to make long-term geophysical observations on the seafloor. In this frontier project, we propose to collaborate with UNAVCO and academic partners to develop, construct, and test prototype integrated and stand-alone seismo-geodetic seafloor instrumentation in order to address two high-priority applications: cross-coastal geophysical studies that can seamlessly extend land-based studies into the offshore environment, and long-term broadband seismic and geodetic observations in remote ocean locations in order to obtain complete global network coverage.

Connecting Big Data to HPC and the "Cloud." Seismology and geodesy are data-rich sciences with a need to access and process terabyte-scale data sets. In this frontier activity, IRIS and UNAVCO propose, in cooperation with the Computational Infrastructure for Geodynamics (CIG) community, to improve support for the geosciences community's use of HPC systems and to provide access to cloud-based systems that are designed to support problems involving very large amounts of observational data.

Workforce and Diversity Initiative. IRIS and UNAVCO propose a new joint Workforce and Diversity Initiative to address the engagement and recruitment of underrepresented groups in the geosciences. IRIS will focus on using urban geophysics as a means of attracting minority students to geophysics by establishing its relevance to the communities in which many students from underrepresented groups live. IRIS will also develop an open access, online geoscience careers module for community colleges and undergraduate institutions aimed at minority students that will be coupled with a new place/problem-based course on urban geophysics to engage first-year students and sophomores.

Over the next decade, the foundational and frontier capabilities summarized above and described in detail in the following pages will enable a new generation of scientific discoveries and empower the next generation of geoscientists to observe and understand the complex, dynamic geosystems that have governed the evolution of our planet in the past and that will control how it will change in the future.

Structure of this Proposal

This proposal is structured to comply with the NSF Proposal and Award Policies and Procedures Guide NSF 16-1, effective January 25, 2016, and the requirements of solicitation NSF-16-546.

In Section 3 of this Project Description, we describe the breadth of science that the NGEO facilities will support and the facility capabilities required to address key scientific questions in four broad topical areas defined in community science plans and documents: (1) Global Earth Structure and Dynamics, (2) Fault Zones and the Earthquake Cycle, (3) Magmas and Volatiles in the Crust and Mantle, and (4) Hydrosphere, Cryosphere, and Atmosphere. In Section 4, we outline the broader societal impacts of the NGEO facilities and the science they support. In order to describe the complete scope of research the NGEO facilities will support, and their value to society, Sections 3 and 4 have been jointly authored by IRIS and UNAVCO, with each organization illustrating the unique scientific contributions and broader impacts of the facilities they are proposing to manage and operate with different figures. Section 5 describes the foundational and frontier facilities that IRIS proposes to manage and operate as part of the NGEO. For each facility, we describe its vision, mission, and goals; the capabilities it will provide to the scientific community and the research it will support; plans for facility operation over the next 10 years; and facility management and organizational structure. The Project Description concludes with a summary of the contributions we expect the NGEO to make to diversity and workforce development, our risk management and assessment strategies, and plans for NGEO management, governance, and community engagement.

3. Scientific Drivers of the NGEO Facilities

Introduction

Earth system processes operate over a remarkable range of spatial and temporal scales, from microscopic grain boundaries to the thousands of kilometers involved in mantle convection and plate boundaries, and from fractions of a second to billions of years (**Figure SD-1**). Examples include crustal and lithospheric dynamics, mantle convection and the core dynamo, the evolution of fault and volcanic systems, the charging and depletion of aquifers, glacier dynamics and glacial isostatic adjustment, the response of the Earth system to land use and climate change, the dynamics of water in the troposphere, and excitation of the ionosphere by terrestrial and solar events.

Seismic, geodetic, and other related geophysical observations are powerful tools for studying these diverse Earth system processes over the range of spatial and temporal scales at which they operate. The facilities needed to make these observations are essential to advancing basic understanding of these processes, but also have broader societal relevance for understanding and mitigating risks from geohazards, informing environmental planning and management, developing new methods for energy exploration, contributing to national security, and providing geospatial and positioning services to a broad constituency of users. National geophysical facilities also support efforts to attract students to geoscience careers, broaden participation from underrepresented groups, and engage the general public's interest and understanding of the planet on which we live.

In the sections that follow, we briefly outline how geodetic, seismic, and other geophysical observations have advanced our understanding of fundamental Earth system processes, and identify the facility capabilities that will be required to enable new discoveries and understanding of multiscale Earth system dynamics in the next decade and beyond.

Global Earth Structure and Dynamics

Improvements in resolution of the three-dimensional structure of Earth's interior, combined with enhanced measurements of motion and deformation at Earth's surface, are key to improving our understanding the dynamic processes that drive plate tectonics and result in natural hazards, such as earthquakes, tsunamis, and volcanic eruptions. Because Earth's deep interior is inaccessible, fundamental questions remain about the forces and feedbacks that govern convection in the core and mantle, how convective flow couples to the lithospheric plates, and how it affects surface processes (e.g., Lay, 2009; NRC, 2012).

The accuracy, resolution, and accessibility of the tools that allow us to investigate the structure and dynamics of Earth's interior are rapidly improving. High-fidelity, well-calibrated seismic, electromagnetic, and geodetic sensors are increasingly portable and rugged so that spatially extensive, dense arrays of instruments can be deployed in even the harshest environments. Geodetic measurements now provide millimeter precision, post-processed, daily positioning globally, while a new generation of relatively inexpensive

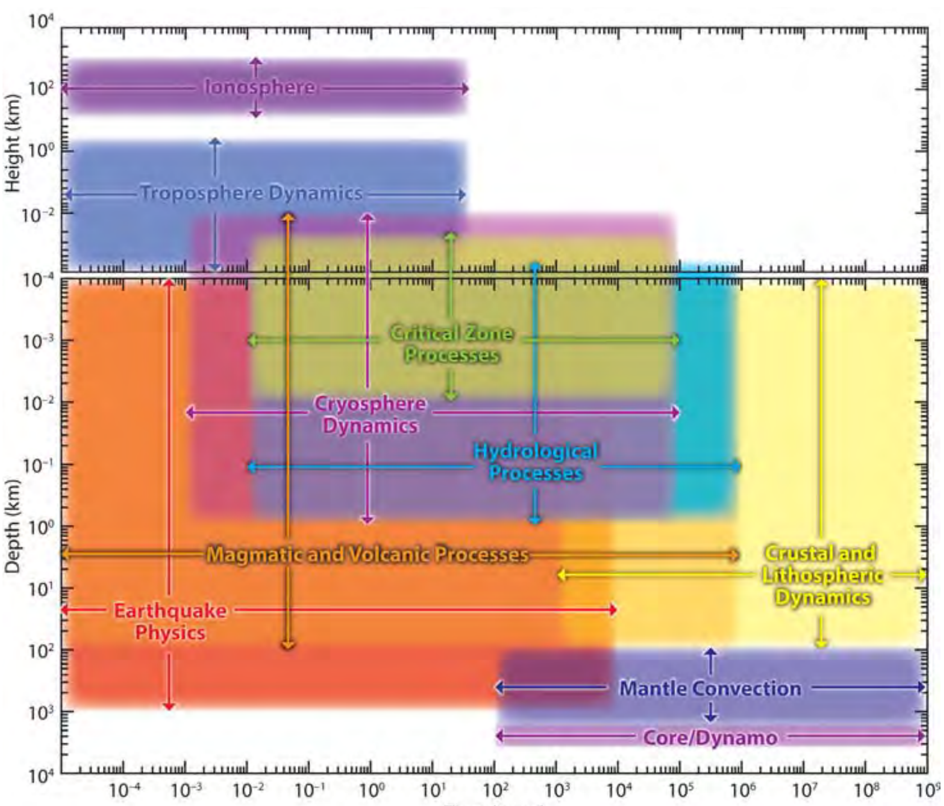
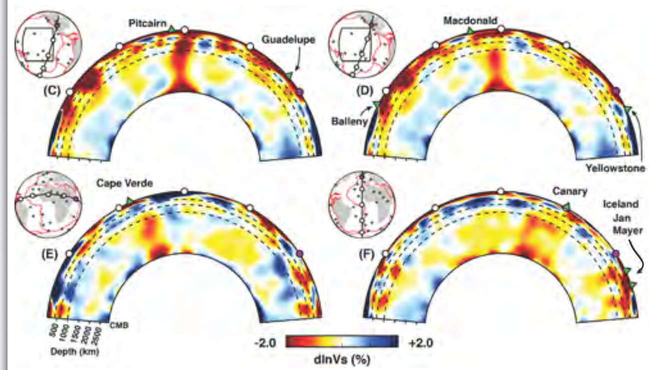


FIGURE SD-1. Earth system processes operate over an incredibly wide range of spatial and temporal scales, from microscopic grain boundaries to the thousands of kilometers involved in mantle convection, and from fractions of a second to billions of years. Seismic, geodetic, and other geophysical observations are powerful tools for studying these diverse Earth system processes over the many spatial and temporal scales at which they operate.

portable "posthole" seismometers can obtain close to observatory-quality data. It is now possible to routinely capture large volumes of geophysical data at high sample rates, store them in quality-controlled, publicly available archives, and deliver these data to the desktop of any interested researcher worldwide, much of it in real time. Advances in both computational resources and the development of sophisticated, multiparameter dynamical models allow integration of these varied geophysical data sets with each other and with other observations from geochemistry, rock physics, geomorphology, and geology. Over the next decade, this rapidly evolving geophysical infrastructure will enable fundamentally new ways of studying Earth's interior and the wide range of interacting processes that have controlled its structure and evolution over 4.5 billion years of Earth history.

The next decade of research will see increasing use of multiparameter 3-D reference Earth models that will cross formal disciplinary boundaries between geodesy, seismology, and geodynamic modeling, as researchers try to quantify lateral variations in density, temperature, and rheology within Earth, and explore how dynamic forcing on the surface and in the interior are reflected in geodetic, seismic, and related observations. Underpinning all modern global geophysical studies is the definition of the global terrestrial reference frame. The International Terrestrial Reference Frame is the premier terrestrial reference frame used today and defines Earth's geocenter and its motion with time. ITRF14 provides the context for comparing and combining geodetic observations around the globe (e.g., NRC, 2010) that provide the data to analyze current plate motions (DeMets et al., 2010), plate boundary dynamics (McCaffrey et al., 2016), fault zones and the earthquake cycle (Melgar et al., 2015b), and related problems. Over the next decade, geophysical research will increasingly link geodetic and seismic measurements of the kinematics and dynamics of Earth's surface and interior (e.g., convection, descending slabs).

Imaging Earth's Deep Mantle



The relationship of major hotspot volcanoes, like Hawaii, observed at Earth's surface, to large-scale convection in the mantle has been a subject of controversy for decades. These vertical cross sections through Earth's mantle showing percent deviation in shear velocity (Vs) relative to the global average at each depth across prominent hotspots in the Pacific (top panels) and Atlantic (bottom panels) have provided new insight into this long-standing scientific question. Broad, low-velocity, quasi-vertical conduits (red) extend from the base of the mantle to major hotspot volcanic centers at Earth's surface. These plumes are rooted at the base of the mantle in large, low shear velocity provinces centered under the Pacific Ocean and under Africa that may contain zones of ultra-low velocity. In order to better document the fine-scale structure around key features in the mantle, such as the possible existence of ultra-low velocity zones at the roots of the plumes, or the deflection of these plumes around the rheological transition at 1000 km depth, it will be necessary to combine "backbone" data from the Global Seismographic Network to constrain the background structure, with dense broadband array data at key locations around the world. *From French and Romanowicz (2014)*

Structure of the Deep Mantle and Core. In recent decades, improvements in the quantity and quality of data from globally distributed broadband seismic stations and arrays, development of new techniques for modeling the seismic wavefield in complex media, and increases in computing capabilities have opened new horizons in global imaging of Earth's interior. This is illustrated, for example, by our improved ability to image broad, low-velocity, plume-like, quasi-vertical conduits in the deep mantle that connect the base of the mantle to major hotspot volcanoes observed at Earth's surface (see **sidebar**). The origin of hotspot volcanoes has been the subject of vigorous debate for the last 30 years, and these new observations indicate at least some hotspots originate in the deep mantle. The fate of subducting slabs is another long-standing scientific question, and new observations clearly show that some subducting slabs appear to stagnate above the 660 km discontinuity and around 1000 km, while others extend into the deep mantle (e.g., Albarède and van der Hilst, 2002; Grand, 2002).

The very long wavelength isotropic structure of the deep mantle is also now becoming better constrained (see **sidebar**). The deep mantle is dominated by two large low shear velocity provinces centered under the Pacific Ocean and under Africa, respectively, surrounded by a ring of fast velocities that are thought to represent the graveyard of subducted slabs (e.g., Moulik and Ekström, 2014; French and Romanowicz, 2014). With the availability of data from EarthScope's Transportable Array and other regional and global broadband seismic networks, evidence is also accumulating for the presence of ultra-low velocity zones at the base of the mantle where seismic velocity is reduced by 20% or more relative to the surrounding regions. Some of these ultra-low velocity zones may be up to 1000 km wide (Cottaar and Romanowicz, 2012; Thorne et al., 2013) and are located at the roots of zones of upwelling such as the Hawaiian hotspot. These regions are a key component for explaining patterns of mantle convection and plate tectonics. However, their thermochemical nature, vertical extent, and fine-scale structure, all of which could inform their role in global mantle circulation are still vigorously debated.

Evidence for complexity in the structure and anisotropy of the inner core is also growing (e.g., Deuss, 2014). For example, hemispherical structure within the inner core supports dynamical models of lopsided freezing and melting at the inner-core boundary. Boundary layers in the outer core are of particular interest in light of revised estimates of core thermal conductivity (e.g., Gubbins et al., 2016), because of their potential importance for understanding core dynamics and the generation of Earth's magnetic field. The detailed seismic structure of these regions, possible lateral heterogeneity within them, and the topography of the corresponding fluid-solid boundaries are still poorly known.

Earth rotation encompasses both the motion of Earth's rotation axis relative to the inertial or celestial frame, as well as the change in the angular velocity about the rotation axis. Earth rotation, and the specific location of the geocenter, is also influenced by mass distribution within the solid Earth and its fluid envelopes. Geodetic nutation observations, for example, can be used to constrain structure and interactions at the core-mantle boundary (e.g., Dehant and Mathews, 2015). The speed of Earth's rotation, expressed as "length of day" (LOD), changes on a large range of time scales. It has long been known that LOD at annual and subannual time scales is impacted by the exchange of angular momentum between the solid Earth and the atmosphere and ocean (e.g., Gross, 2015). LOD variations at a 5.9-year period, however, are strongly coherent with occurrence times of geomagnetic jerks, thereby constraining electrical conductivity (and therefore composition and structure) of the lower mantle (Holme and de Viron, 2013). The response of the solid Earth to tidal forcing, as constrained by global high-accuracy geodetic observations, can also provide important constraints on large-scale density variations within the mantle (Latychev et al., 2009; Yuan et al., 2013).

Unraveling the detailed structure of Earth's deep mantle and core, essential for understanding the planet's global dynamics and thermal evolution, requires focused imaging using dense arrays of broadband seismometers distributed in various regions of the world. Temporary deployments of dense arrays, augmented by seafloor observations, allow representative sampling of the deep Earth. However, the temporary nature of these seismic arrays requires permanent global networks such as the GSN, with its standardized high-quality instrumentation and accumulation of data over many decades, to tie regional models together to the same reference Earth model.

Lithospheric Structure and Plate Boundary Dynamics. The physical and chemical properties that make the lithosphere "plate-like" and the coupling between the lithosphere and the convecting, weaker mantle below (the asthenosphere) are an ongoing focus of geoscience research. The roles of water, CO_2, small degrees of partial melt, and grain-scale deformation in creating a weak asthenosphere are vigorously debated, with essential constraints provided by high-resolution models of seismic velocity, anisotropy, attenuation, electrical conductivity, and geodetic determination of density variations and surface deformation. The structure and strength of the lithosphere and underlying mantle control its response to internal and external stresses that deform the Earth. The interaction of structure with dynamic forcing defines plate boundary dynamics and the earthquake cycle, along with the mechanical properties of fault zones (see next section). We are gaining new insight into the accommodation of plate boundary motion on faults in the shallow crust and shear zones that reach the base of the lithosphere. In continental rifts, marked variations in the style and degree of deformation in the crust and mantle lithosphere point to interplay between mechanical and magma-assisted deformation (e.g., Ebinger et al., 2010; Hansen and Nyblade, 2013; Stamps et al., 2015).

EarthScope observations are transforming models of lithosphere-asthenosphere processes beneath the United

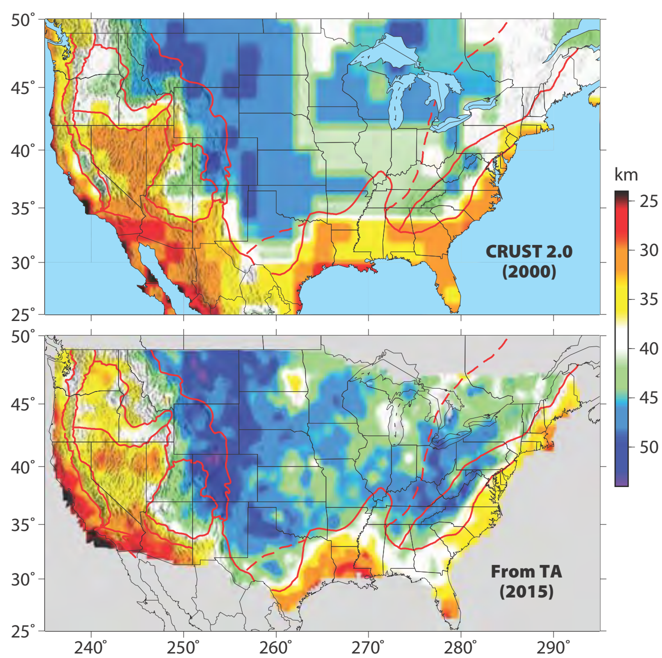
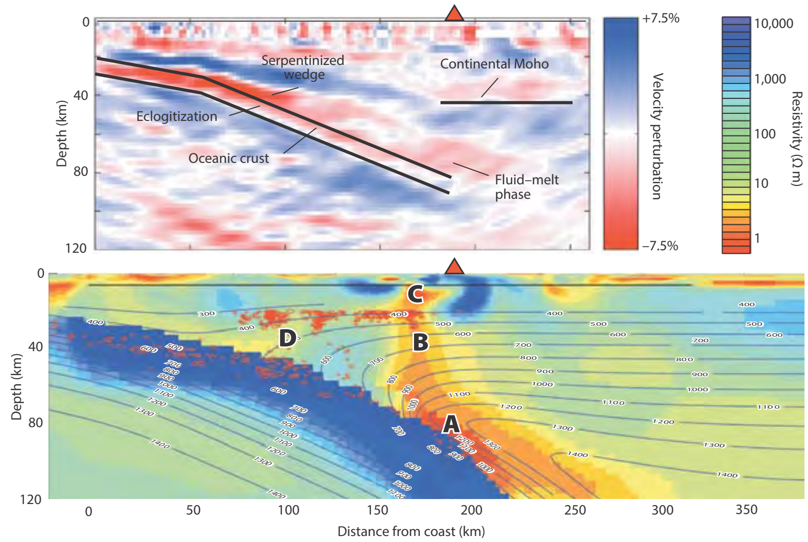


FIGURE SD-2. The EarthScope Transportable Array and other dense array deployments are transforming models of lithosphere-asthenosphere processes beneath the United States. The top panel shows crustal thickness across North America based on the CRUST2.0 model (Bassin et al., 2000). The bottom panel shows the results of new crustal thickness measurements that used ambient noise and surface wave group velocity measurements and teleseismic earthquake receiver functions (Shen and Ritzwoller, 2016). In some regions, crustal thickness measurements were revised by >10 km, and the resolution of variations in crustal thickness improved considerably across all of North America. *Figured adapted from Shen and Ritzwoller (2016).*

Subduction Zone Processes

The combination of seismic and magnetotelluric data are providing fundamental new constraints on the processes of slab dehydration and magma generation, ascent, storage, and eruption in subduction zones. Shown here is an interpreted seismic tomographic section across the Cascadia subduction zone and a co-located resistivity and thermal model derived from a magnetotelluric experiment. Fluid released from the subducting slab enters the mantle wedge at A. Melt initiated at or very near the top of the subducting slab is transported upward by buoyancy and dragged down. The fluid/melt phase rises through the mantle wedge (B) until it reaches the crust, joining fluids released from shallower reactions (D). The combined fluid/melt continues to rise until reaching a magma chamber (C) in the crust. Mount Rainier is shown as a red triangle. *From McGary et al. (2014)*



States. The Transportable Array, along with improvements in array analysis techniques that make use of these well-calibrated data sets (Cafferky and Schmandt, 2015), now illuminate Earth's interior at unprecedented resolution (e.g., Schmandt and Lin, 2014; Shen and Ritzwoller, 2016; **Figure SD-2**), and boundaries within Earth are now constrained with much higher precision using scattered and reflected seismic waves (e.g., Levander and Miller, 2012; Hansen et al., 2015; Hopper and Fischer, 2015). The Plate Boundary Observatory, and associated GPS networks in Mexico and the Caribbean (e.g., Meqbel et al., 2014; Becker et al., 2015), have provided a synoptic view of the surface velocity and strain field, quantifying the kinematics of plate boundary deformation. The combination of seismic and magnetotelluric data are providing fundamental new constraints on the processes of slab dehydration, magma generation, ascent storage and eruption (McGary et al., 2014; **sidebar**).

In the ongoing continental collisions that form the great present-day mountain belts, such as the Himalayas and Alps, seismic imaging involving broadband regional arrays, active source experiments, and GPS-derived surface deformation have revealed crustal detachments that extend over hundreds of kilometers (e.g., Reilinger and McClusky, 2011; Caldwell et al., 2013; Elliott et al., 2016). However, major questions remain about the processes of crustal deformation and the fate of the colliding lithosphere. Knowledge of how mountain belts evolve is key to understanding both lithospheric dynamics and how topography interacted with past climate. Signatures of subduction-like processes are revealed in ancient cratonic lithosphere that is billions of years old (e.g., Chen et al., 2009; Hopper and Fischer, 2015). Future progress on these and other pressing tectonic-scale questions requires easily deployed portable seismic, geodetic, and magnetotelluric instruments that can be flexibly configured into experiments at varying scales, including dense seismometer arrays that permit unaliased sampling of seismic wavefields, complemented by continuous GNSS networks.

Fault Zones and the Earthquake Cycle

Earthquake shaking and secondary effects such as landslides, tsunamis, and liquefaction, and their effect on the built environment, constitute some of Earth's most destructive natural hazards. The recognition that long-term plate motions reorganize and deform Earth's surface provided a breakthrough in understanding the nature of earthquakes and earthquake cycles. Earthquakes involve accommodation of tectonic motions by shallow brittle and deeper ductile fault slip in Earth's lithosphere; repeated events must keep pace with long-term plate motions. The earthquake cycle is characterized by long periods of interseismic elastic strain accumulation punctuated by transient deformation and coseismic rupture, ground vibration and deformation, redistribution of stress, and subsequent fault zone healing. At greater depths and temperatures, time-dependent earthquake cycle deformation occurs by aseismic ductile flow of rocks (e.g., Bürgmann and Dresen, 2008). Transient postseismic relaxation and stress changes from great earthquakes can endure for decades and affect areas hundreds of kilometers away from the main rupture (Wang et al., 2012). Seismic and geodetic measurements enable improved understanding of the physics of earthquakes and the associated cycle of elastic and inelastic deformation. High-resolution imagery of fault topography in combination with detailed geophysical images of the subsurface allow us to characterize the integrated near-field damage from past earthquake ruptures.

The past decade has witnessed numerous great subduction zone earthquakes that have provided unprecedented geophysical observations. We now have the first digitally recorded ground motions from M_w>9 earthquakes at global observatories with high quality, permanent geodetic and seismic stations (Subarya et al., 2006; Simons et al., 2011; Lay et al., 2012). For great earthquakes worldwide, further constraints on pre- and post-seismic deformation come from continuous GPS, satellite interferometric synthetic aperture radar (InSAR), and satellite optical imagery, together with remarkable deepwater tsunami observations from ocean-bottom pressure sensors and seafloor geodesy. Study of these great earthquakes is a prime example of the importance of the combined use of geophysical data sets to maximize spatial and temporal resolution of fault slip behavior prior to, during, and following a great earthquake (**Figure SD-3**). Well recorded, but smaller continental earthquakes allow very detailed quantification of the deformation processes associated with earthquakes, as well as improvements in our understanding of how stress evolves within complex fault zones and associated hazard implications.

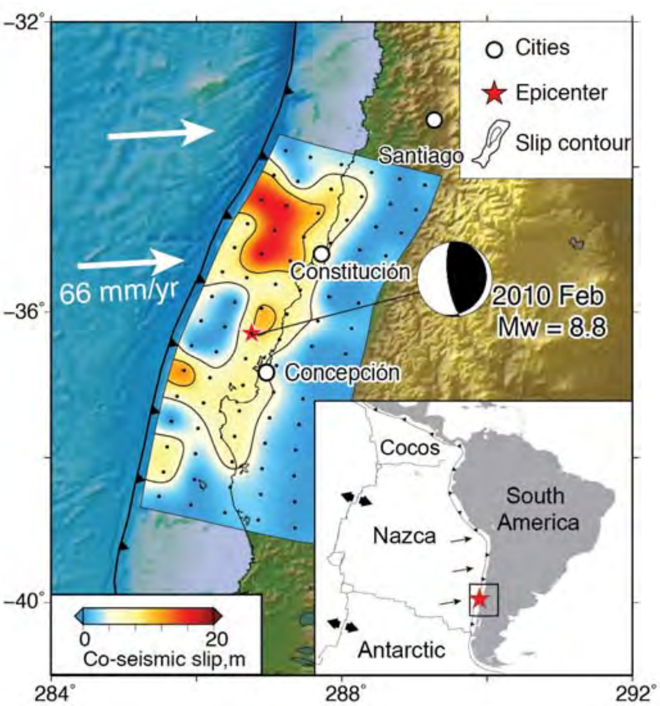


FIGURE SD-3. Combined use of seismic, geodetic, and InSAR data is providing new constraints on fault slip behavior prior to, during, and following an earthquake. The main map shows the Global Centroid-Moment Tensor best double-couple solution for the February 27, 2010, M_w 8.8 Maule, Chile, earthquake. The earthquake slip determined by inversion of teleseismic body waves, high-rate GPS, static GPS offsets, InSAR, and tsunami data is shown with a blue-red scaled contour map with 5 m and 10 m slip contour lines. Center locations of each subfault used in the inversion are marked with black dots. *From Yue et al. (2014)*

Fault slip behavior is now recognized to be much richer than was thought just a decade ago, creating the potential to characterize fault frictional behavior with further multidisciplinary study of fault zones. High-quality geodetic observations from permanent GPS networks enabled the discovery of slow slip events (Hirose et al., 1999; Dragert et al., 2001) and, in Cascadia, their periodicity (Miller et al., 2002). Seismology demonstrates that slow slip is frequently associated with tremor (**Figure SD-4**). Slow slip events occur over a wide spectrum of spatial and temporal scales and are found from near the surface to well below the seismogenic portion of a fault (Beroza and Ide, 2011). Slow slip can be triggered by teleseismic waves, tides, and surface loads, and has been observed to occur just prior to some large earthquakes (e.g., Kato et al., 2012; Brodsky and Lay, 2014). For subduction zones, characterizing the full spectrum of deformation processes will require dense onshore and significantly expanded offshore instrumentation deployed at multiple regions using seismic, geodetic, magnetotelluric, controlled-source electromagnetic, and geological investigations. Long-term measurements made over a wide range of spatial and temporal scales are essential for quantifying the elastic, anelastic, and transient (e.g., creep events, afterslip, poroelastic rebound, viscous relaxation) processes acting in fault systems. Elucidating the complex, time-variable behavior of slip underlies much of the collaborative efforts of the seismology, geodesy, geology, and hazard communities, for example, as implemented by the efforts of the joint NSF-USGS Southern California Earthquake Center.

Advances in studies of the earthquake cycle depend on the existence and enhancement of permanent dense geophysical networks, as well as an expanding range of remote-sensing technologies that can capture deformation and seismic waves over a wide range of spatial and temporal scales. The study of earthquake nucleation relies on observations, theory, and lab experiments, yet direct observation of the nucleation phase in active fault systems remains elusive. Intriguing results from some earthquake sequences suggest that enhanced observations using new sensor technology (high-sample-rate GPS, dense seismometer arrays, offshore sensor networks) with increased sensitivity over a broad range of environments, including the seafloor, could fuel significant progress in understanding the earthquake cycle (Obara and Kato, 2016).

Another major challenge in studies of earthquake behavior is the possibly inherent unpredictability of great earthquakes. One strategy takes advantage of the space-time clustering of earthquakes and focuses on those areas with significant recent changes in earthquake activity. This strategy requires a large, flexible, and readily deployable instrument pool, including rapid response elements. Upon earthquake initiation, seismogeodesy can rapidly characterize rupture kinematics and dynamics (Melgar et al., 2015a), holding promise for early

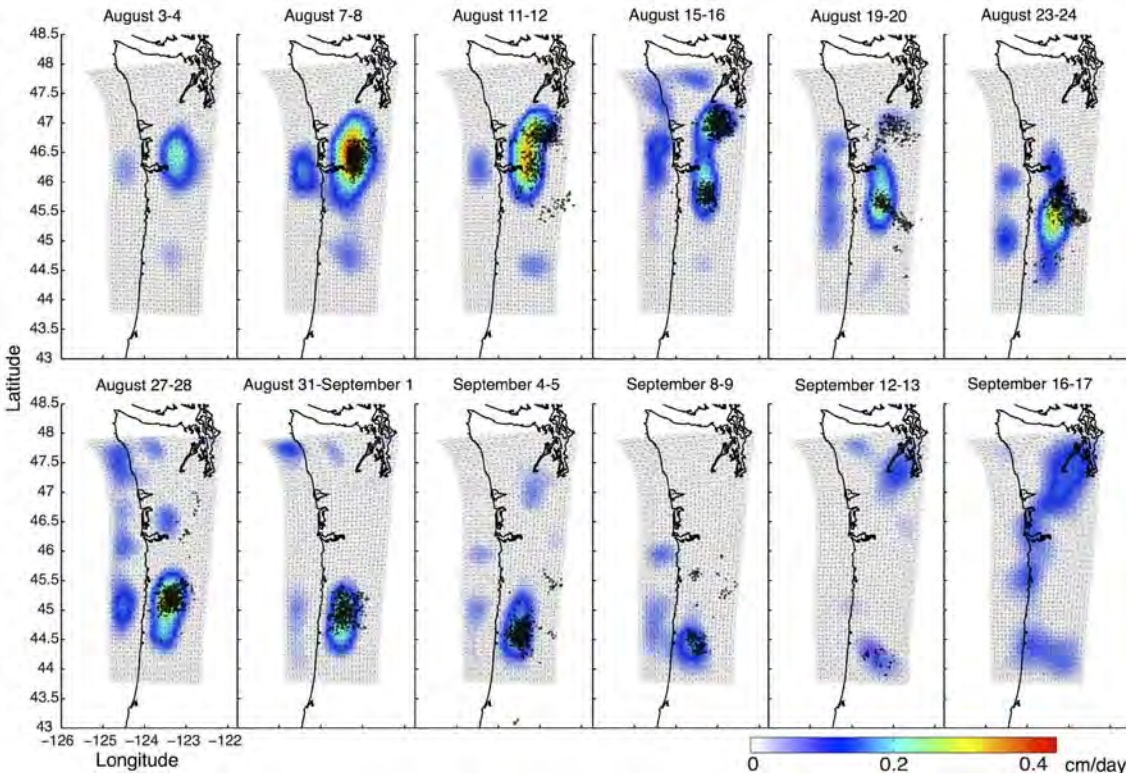


FIGURE SD-4. Fault slip processes are now recognized to be much richer in behavior than was thought just a decade ago. Slow slip and tremor from continuous GPS and seismic records during a 2009 M_w 6.9 slow-slip event deep in the Cascadia subduction zone are shown here. The slip rate on the plate interface is averaged over two-day intervals. Black dots indicate tremor epicenters in the same two-day intervals. *From Bartlow et al. (2011)*

detection and robust characterization of coseismic moment release to inform early warning systems, rapid response, and situational awareness.

Magmas and Volatiles in the Crust and Mantle

Geophysical instrumentation is crucial for studying melt production in the mantle and its transport through the crust to volcanoes at Earth's surface, as well as the shallow plumbing systems of magma and volatiles that control eruption dynamics and duration. Better understanding of volcanic systems afforded by increasing instrument quality and density will be essential for minimizing risks related to volcanic hazards and formulating societal response to future volcanic activity.

Unlike some other natural hazards, volcanic eruptions are often preceded by hours to years of observable unrest, such as increased seismicity, deformation, and/or gas emissions (Sparks et al., 2012). A "restless" volcano offers opportunities to map shallow magmatic plumbing systems and observe processes related to the ascent and accumulation of magma and gases, and resulting deformation. For example, deep, long-period earthquakes are associated with magma ascent from the mantle into the lower crust both prior to and during eruptions (Power et al., 2004), shallow volcanic-tectonic seismicity reflects changes in crustal stress due to magma storage and transport (Roman and Cashman, 2006), and surface deformation constrains the geometries and volumes of crustal magma accumulation (e.g., Dzurisin, 2003). During the 2002–2009 unrest at Mauna Loa, Hawaii, for example, deep, long-period earthquakes at mantle depths preceded and accompanied shallow seismicity and crustal inflation, highlighting the volcano's plumbing system nearly from the magma source to just beneath the surface (Okubo and Wolfe, 2008).

At the root of most investigations of volcanic activity is the need to understand the source of episodic unrest that sometimes culminates in an eruption (e.g., Long Valley, California; Yellowstone, Wyoming; and Campi Flegrei, Italy). The mechanisms of episodic caldera unrest are a matter of debate, as is the nature of the fluids that drive intense seismicity and rapid caldera uplift. Time-variable microgravity has shed some light on this problem by providing constraints on source density. Combined gravity and deformation measurements obtained during the 1980s and 1990s have suggested that magma drove unrest at Long Valley (Battaglia et al., 1999), while hydrothermal fluids played a role at Campi Flegrei (Battaglia et al., 2006), and both magma and hydrothermal fluids drove changes in seismicity and deformation at Yellowstone (Tizzani et al., 2015).

Even at volcanic systems that are not experiencing an episode of unrest, geophysical imaging techniques have repeatedly proven useful for mapping magma reservoirs in the mid to shallow crust. Both GPS networks and synoptic InSAR imagery enable detailed mapping of surface deformation in response to changes in magma reservoirs. At local scales, seismic tomography can be used to estimate melt volume and provide constraints on the crustal magma plumbing system

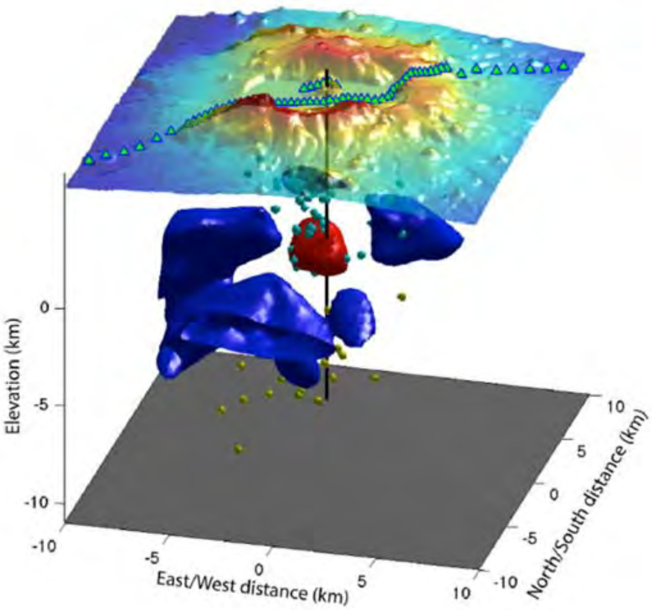


FIGURE SD-5. Seismic tomography using both explosive and earthquake sources can be used to estimate volumes of melt and provide constraints on the crustal magma plumbing system. In this 3-D perspective view of tomography results from Newberry Volcano, Oregon, dark blue indicates areas of higher velocity interpreted as cooled intrusive rocks. The red volume denotes areas of lower velocity inferred to be a magma body. Subcaldera earthquakes are noted by small blue spheres recorded during 2012–2015, and small yellow spheres are deep, long-period earthquakes. *From Heath et al. (2015)*

(Larson, 2013). InSAR data, most often used to characterize surface deformation over swaths of tens to hundreds of kilometers, can also be used to map lava flow activity day or night and regardless of cloud cover based on coherence over time (Dietterich et al., 2012) and SAR amplitudes can measure volcanic dome growth over time (Surono et al., 2012).

Geophysical imaging also plays an important role in solving the multidisciplinary problem of the origin of melt in the mantle. Close comparison between seismic images and petrological/geochemical indicators of melting temperature and depth show that regions of melt production in the mantle display exceptionally low seismic velocities (**Figure SD-6**; Syracuse et al., 2008; Long et al., 2012; Wei et al., 2015; Plank and Forsyth, 2016). This makes it possible to infer the depth and spatial extent of melt production in the mantle and constrain the mechanism by which mantle melt is collected and focused into volcanic systems and spreading centers.

Key to advancing understanding of volcanic systems will be to combine in situ measurements (e.g., petrologic studies of erupted lavas) with high-quality, multiparameter geophysical data (e.g., geodetic, seismic, magnetotelluric) from both campaign and continuous networks and remote-sensing systems to track pre-, co-, and post-eruption changes. The study of active volcanic systems requires the ability to rapidly deploy instrument networks, often in difficult and hazardous terrain.

(**Figure SD-5**; Voight et al., 2010; Paulatto et al., 2012; Heath et al., 2015). Furthermore, analysis of ambient seismic noise has proven valuable for detecting subtle changes in rock properties around a pressurizing magma reservoir, even in the absence of local seismic activity (e.g., Brenguier et al., 2008). At much broader scales, seismic velocity and magnetotelluric data can image melt generation in subduction environments—from fluid release from the slab to melt transport into crustal storage reservoirs (see **sidebar on page 11, lower panel**).

Diverse geophysical methods provide additional unique constraints on volcano dynamics. For example, infrasound has demonstrated exceptional ability to detect volcanic signals, and also characterize eruption style and dynamics (Fee and Matoza, 2013). GPS signal strength can be used to detect surface deformation through positioning measurements, but can also detect volcanic plumes, and does not require complex processing. It is not limited by time of day or weather conditions, suggesting that it may be possible to implement terrestrial real-time ash detection algorithms for improved volcano monitoring and hazards assessment

Hydrosphere, Cryosphere, and Atmosphere

The hydrosphere, cryosphere, and atmosphere cloak the solid Earth with protective fluid envelopes that moderate climate and sustain life. Water, both as liquid and vapor, moves between the solid Earth, its regolith, and the atmosphere,

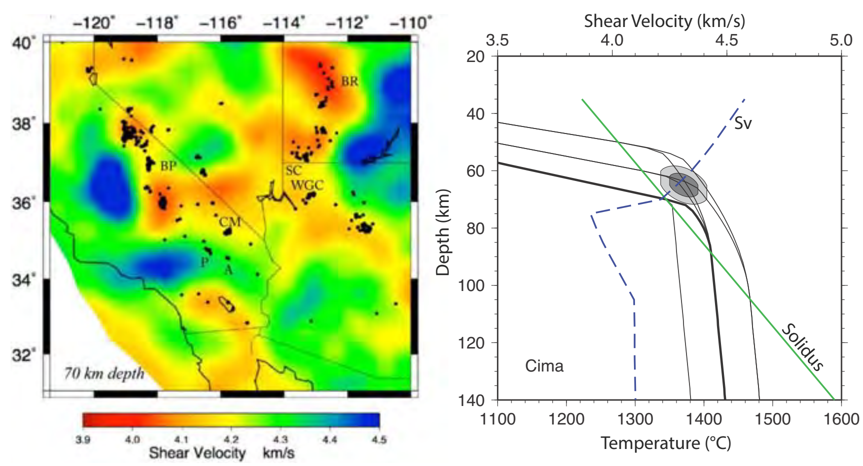


FIGURE SD-6. Regions of melt production in the mantle display exceptionally low seismic velocities. (left) Seismic shear velocity at 70 km depth beneath the Basin and Range province in the western United States from Rayleigh waves recorded at EarthScope Transportable Array seismic stations. Black dots represent volcanic vents active within the last million years. (right) Results from joint inversion of seismic and petrologic data for the thermal structure and P/T conditions of melting for the Cima volcanic field (labeled CM on the map). The light gray ellipse is the 95% confidence limit for the melt equilibration depth and temperature, based on the petrological thermobarometer. *From Plank and Forsyth (2016)*

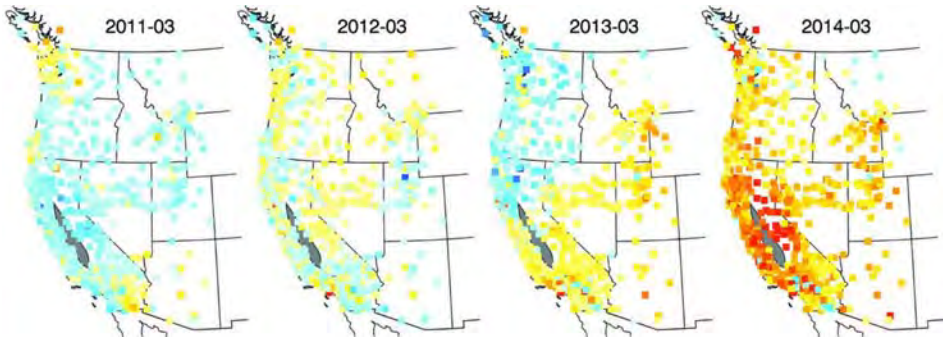


FIGURE SD-7. Deformation of Earth's surface measured by GPS can be used to estimate water mass variations in subsurface aquifers on short temporal and spatial scales. Shown here is the spatial distribution of vertical displacements from March 2011 through 2014. Uplift is indicated by yellow-red colors and subsidence by shades of blue. Note uplift bordering the California Central Valley as the underlying water is withdrawn for irrigation during the recent drought. *From Borsa et al. (2014)*

in part modulating energy transfer. Some water transfer boundaries within these spheres are relatively sharp, such as at the sea surface and seafloor, but most are more diffuse, such as in the critical zone or the base of a glacier that mixes rock, ice, and water.

Near-Surface and Surface Hydrology. Rainfall and snowmelt are temporarily held at Earth's surface as soil moisture before returning to the atmosphere via evapotranspiration, flow into rivers, or stored in groundwater reservoirs. NASA's Gravity Recovery and Atmospheric Change Experiment (GRACE) mission provides estimates of terrestrial water storage using time-variable observations of gravity from orbit, but these data only represent coarse spatial (>400 km) and temporal (monthly) scales (Rodell et al., 2009; Famiglietti et al., 2011). Recently, deformation of Earth's surface measured by GPS has been used to estimate water mass variations on much shorter temporal and spatial scales (Amos et al., 2014; Argus et al., 2014; Borsa et al., 2014; Chew and Small, 2014), making it possible to study the water cycle at a scale more consistent with challenges facing society (**Figure SD-7**). Integration of GPS-based loading estimates with more traditional hydrologic observations, and with surface deformation measured by InSAR, permits an understanding of the processes that bring about changes in water storage as groundwater, as snow, or in soil (Ouellette et al., 2013; Chew and Small, 2014; Fu et al., 2015).

Typical ground-based tools for measuring water content in snow, soil, and vegetation have sampling footprints that are limited in spatial extent (~1 m^2), so local observations may not always be representative of conditions across a watershed. GPS Interferometric Reflectometry (GPS-IR) has been developed to estimate hydrologic variables using reflected GPS signals with a sensing footprint of 1000 m^2 (Larson et al., 2008, 2009; Small et al., 2010). Near-surface geophysical methods, especially ground penetrating radar, can be used to quantify snow-water equivalent, snowmelt, and snow redistribution processes over large areas (Marchand and Killingtveit 2005; Holbrook et al., 2016). These new kinds of observations of surface water storage bridge the gap between in situ observations and remote-sensing estimates, providing a unique perspective to study processes of snow accumulation and melting.

Critical Zone Processes. The surface and near-surface environment, dubbed the "critical zone," is Earth's breathing skin, a porous "membrane" spanning tree canopy to bedrock, across which life-sustaining chemical and mass fluxes occur and where bedrock is transformed into soil (e.g., Anderson et al., 2007; Brantley et al., 2007; Chorover et al., 2007; **Figure SD-8**). The NSF has established 10 Critical Zone Observatories (CZOs) at which biogeochemical, hydrological, and physical processes in the critical zone are studied intensively in a variety of settings. The CZOs address questions about landscape evolution, bedrock weathering, soil formation, carbon budgets, moisture availability, nutrient cycling, surface water-groundwater interactions, and feedbacks among those processes. It is clear, for example, that the vertical and lateral distribution of porosity and permeability

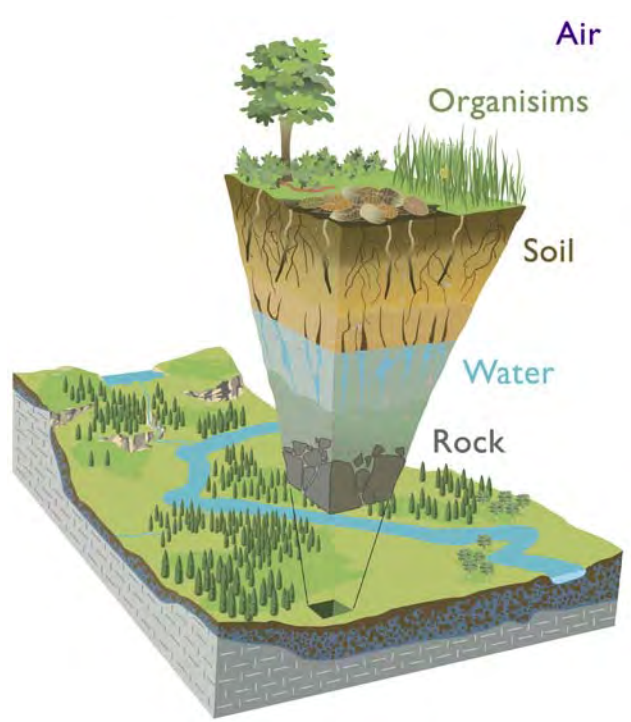


FIGURE SD-8. The critical zone, Earth's outermost layer spanning treetops to bedrock, hosts an array of interacting biological, physical, hydrological, and geological processes that transform bedrock into soil and affect landscape evolution, carbon budgets, moisture availability, nutrient cycling, and surface water-groundwater interactions.

in the subsurface varies within and between watersheds, strongly affecting the relationships between precipitation, recharge, and runoff (St. Clair et al., 2015).

Remote-sensing methods, including lidar, InSAR, and GNSS are revolutionizing our ability to image Earth's surface and measure mass fluxes and short-term deformation, essential observations for understanding the critical zone. There is growing recognition that a comprehensive characterization of the critical zone requires the application of geophysical techniques (Riebe and Chorover, 2014). In particular, geophysical surveys aimed at critical zone processes have begun to elucidate controls on the architecture of the critical zone (e.g., Befus et al., 2011; Parsekian et al., 2015), its relationship to high-resolution surface topography (St. Clair et al., 2015), and the development of subsurface porosity that sustains vegetation (e.g., Holbrook et al., 2014). Advancing understanding of critical zone processes requires specialized geophysical instrumentation, technical expertise, and training for near-surface, high-resolution geophysical studies not currently available in any national, multi-user geophysical facility (Aster and Simons, eds., 2015).

Sea Level Change. The dominant contributors to global sea level rise are thermal expansion of the world ocean and melting of glaciers (Church et al., 2013). Earth's great ice sheets contain enough water to raise global mean sea level by 62 m, although sea level rise is not uniform around the world due to changes in the gravity field and glacial isostatic adjustment (Riva et al., 2010). Since the early 1990s, melting in Greenland and Antarctica has increased global sea level rise from 1.7±0.2 mm/yr (1901–2010) to 3.2±0.4 mm/yr (1993–2010) (Church et al., 2013). Ice loss in Greenland and western Antarctica is also accelerating (Velicogna, 2009; Kahn et al., 2016), commonly attributed to a warming ocean. Because human population is concentrated in coastal regions, the societal impact of sea level rise over the next century will be enormous. Should current trends go unmitigated, one expert assessment indicates sea level will rise 0.7–1.2 m by the year 2100 and 2.0–3.0 m by the year 2300 (Horton et al., 2014).

Regional variation in long-term sea level rise can be significantly larger over both short and long time scales, as demonstrated along the North Atlantic U.S. seaboard (Sallenger et al., 2012). In the western Pacific, the effects of interdecadal, decadal, and global 60-year oscillations (Chambers et al., 2012) account for part of the increased rate of sea level rise observed there since 1993, but there is also a significant signal attributed to the El Niño-Southern Oscillation (Palanisamy et al., 2015). Terrestrial water storage also plays a role in the temporal variation of sea level rise (Church et al., 2013). This was dramatically demonstrated during the 2010–2011 La Niña that resulted in so much rainfall over the closed interior basin of Australia, that the water retained on the continent offset the global annual addition of freshwater to the ocean (Fasullo et al., 2013). In fact, interannual variability in sea level is now believed to be fully accounted for by known water storage changes on land and in the atmosphere (Cazenave et al., 2014).

Geodesy provides the basic tools for measuring sea and land level changes to further these studies: satellite altimetry maps the sea surface, and is complemented by historical and modern tide gauges; satellite gravimetry (such as the GRACE mission) is sensitive to the movement of water among its various reservoirs; and ground-based GPS/GNSS is used to observe water surface height and land level changes. Critical to addressing the impact of sea level rise on coastal communities is the need to precisely determine absolute vertical land motion of coastlines as well as to improve both the observation and modeling of sea level due to the changes in gravitational and solid Earth loading forces under conditions of rapid ice sheet surface melt. Constraining sea level change and its variation requires a global suite of geodetic systems, including GPS/GNSS, that work together to provide a reference frame for sub-mm/yr measurements.

Glacier Dynamics. The ice in Earth's polar ice caps and in mountain glaciers exerts a strong regional and global influence on climate and weather, sea level, glacial and fluvial geomorphology, as well as ecological and critical zone systems, and they modulate freshwater seasonally. Glacial systems are highly sensitive to climate. Earth's glacial ice is rapidly declining through ablation and melting, accelerated flow, creation of proglacial lake basins, glacial outburst floods, and the accelerated calving of continental ice into the ocean. The isostatic adjustments due to glacial unloading depend on both the short-term elastic response of the crust to removal of an ice load and the longer-term viscous flow of the underlying mantle. Accurate assessment of glacial isostatic adjustment is critical to establishing the history of glaciation in the polar regions, as well as for calibrating space-based (e.g., GRACE) and other measurements of present-day ice mass balance.

Glacial ice deforms under viscous flow, but behaves as an elastic solid at seismic periods. Its structure and dynamics and its interactions with the lithosphere can be characterized using geodetic and seismic observations. High-rate continuous GPS observations demonstrate that glacial processes acting at short time scales (seconds to days) influence the multiyear stability of glacial systems (Anandakrishnan et al., 2003; Nettles et al., 2008; Wiens et al., 2008). Combined GPS/seismic studies on the Whillans Ice Stream in Antarctica captured the relationship between the long-term (multidecadal) slowing of the ice stream and short-term ice dynamics (abrupt slip events) (**Figure SD-9**; Pratt et al., 2014). GNSS-IR has been used to track seasonal accumulation and firn densification on the Greenland Ice Sheet, leading to improved understanding of seasonal variation in surface mass balance (Larson et al., 2015; Khan et al., 2016). Near-surface geophysical techniques, especially ground-penetrating radar, can resolve the internal structure of glacial ice, as well as the base of the ice

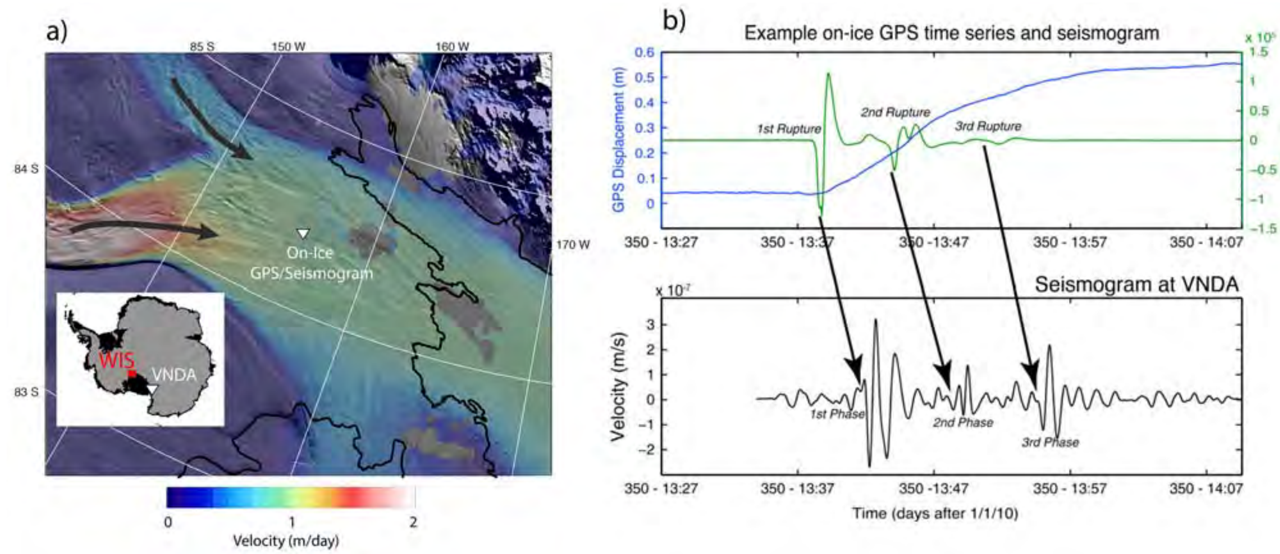


FIGURE SD-9. (a) InSAR-derived surface velocity of the Whillans Ice Stream in Antarctica. Inset shows study area and location of seismic station VNDA. *From Rignot et al. (2011)* (b) Top panel: GPS and seismograph response during ~30-minute stick-slip glacial earthquake. Lower panel: Far-field seismic record from station VNDA (30–100 s). *From Pratt et al. (2014)*

sheet, which controls flow dynamics. Geodetic, gravity, and seismic measurements also provide key insights into the longer-term viscoelastic behavior of the solid Earth, critical to understanding past ice dynamics and predicting future ice dynamics in a changing climate (e.g., Mordret et al., 2016).

Troposphere and Ionosphere. Applications of geodetic and seismic data to characterize the troposphere and ionosphere have expanded rapidly in the past decade, building on previous efforts to interpret satellite-station path delays within the growing array of GPS/GNSS constellations and terrestrial observing networks. GNSS satellite radio signals are sensitive to both scintillation and dispersive delay in the ionosphere, non-dispersive delay due to water vapor, and reduction in carrier phase signal to noise resulting from volcanic ash in the troposphere. Combinations of ground- and satellite-based instrumentation provide key observations for the impact of space weather (scintillation), tsunami-triggered gravity waves in the ionosphere, energy and mass fluxes into and out of the troposphere, and the forcing of weather and climate systems. Seismic deployments that include acoustic sensors can detect infrasound events in the atmosphere associated with both naturally occurring and human-caused events.

While precipitable water vapor products have been generated from GPS observations for decades (e.g., Treuhaft and Lanyi, 1987; Bevis et al., 1992), densification of GNSS-Met networks such as SuomiNet (proposed GPS network providing real-time atmospheric precipitable water vapor measurements), Trans-boundary, Land and Atmosphere Long-term Observations and Collaborative Network (in Mexico) (TLALOCNet), and the Continuously Operating Caribbean GPS Observational Network (COCONet) have further constrained the complex hydrological systems of North American, Mexican, and the circum-Caribbean regions (e.g., Braun et al., 2012; Anthes et al., 2015), which are the sources of devastating hurricanes. The high (>28.5°C) sea surface temperature in the Caribbean influences regional circulation patterns and moisture flow over Central and North America, as well as the El Niño-Southern Oscillation and other larger-scale circulation patterns. Densely spaced terrestrial estimates of tropospheric water vapor, which can be generated in near-real time (every 30 minutes), improve hurricane forecasts (Iwabuchi et al., 2009) and illuminate the climate feedback between sea surface temperatures and water vapor (a key greenhouse gas). Precipitable water vapor estimates in northern Mexico and the western United States are revealing the mechanisms of the North American monsoon, a summer phenomenon that delivers ~40% of the annual precipitation to these dry regions (Serra et al., 2016).

In addition to their inherent scientific value, atmospheric models based on GPS/GNSS data and the associated surface weather stations can be used to improve other observation types that are sensitive to tropospheric water vapor, such as InSAR (e.g., Goldstein, 1995; Emardson et al., 2003; Li et al., 2003, 2005). GPS/GNSS-based corrections of tropospheric water vapor can help InSAR researchers separate signals from tectonics, earthquakes, or anthropogenic activity from signal that arises as a result of radar delays (typically L-band signals close to the frequencies of most GNSS carrier phases) within the atmosphere (e.g., Bekaert et al., 2015; Fattahi and Amelung, 2015) and improve the detection limit for more subtle signals associated with, for example, earthquake swarms and aseismic transients.

Atmospheric acoustics is a rapidly maturing field because of an influx of new data from broadband infrasonic sensors that record low-frequency, large-scale atmospheric signals.

When used in conjunction with microbarometric sensors, the infrasonic sensors yield measurements of pressure changes across the entire frequency band (DC to 20 Hz) used to study a broad suite of atmospheric events from the mesoscale to the local scale. On a local scale, smaller surface pressure features like gust fronts (e.g., Pryor et al., 2014) and downbursts from severe weather events also can be observed. At longer periods, infrasonic and microbarometric data can be used to investigate atmospheric gravity waves, a key mechanism by which the atmosphere distributes momentum and heat energy, but which remain poorly understood because of the lack of high-quality observational data. Infrasound sources also include other naturally occurring events such as rock and debris avalanches, pyroclastic flows, earthquakes and volcanic explosions, iceberg calving, and bolides transiting the atmosphere and disintegrating and also those impacting Earth's surface. Infrasound is also important for detecting and locating nuclear explosions in the atmosphere. The installation of infrasound and microbarometric sensors at global or regional geophysical network stations can, at very low incremental cost, provide data useful in studies of a wide range of solid Earth and atmospheric phenomena.

The ionosphere, the upper portion of the atmosphere, extends from approximately 60 km to 2000 km above Earth. The ionosphere is a weakly ionized plasma that is affected by changes in the solar wind and the ambient magnetosphere, impacting space-based and terrestrial systems, such as telecommunications and electrical power systems. The ionosphere is also home to many complex physical, chemical, and electrodynamic processes, some of which create disturbances at various scales in the ionosphere plasma (e.g., Pi et al., 1997; Basu et al., 2002; Kelley, 2009; Kherani et al., 2012).

Atmospheric gravity waves initiated by large earthquakes and surface waves such as tsunamis can perturb the ionosphere, (e.g., Artru et al., 2005; Occhipinti et al., 2010; Komjathy et al., 2012). GNSS measurements during the 2011 Tōhoku-Oki earthquake provided the first ever ionospheric imaging of the generation and propagation of a tsunami (Liu, et al., 2011; Galvan et al., 2012; Kherani et al., 2012; **Figure SD-10**), demonstrating the potential for using this approach to map offshore propagation of tsunamis and improve methods for detection, validation, and early warning.

GNSS is a capable and cost-effective ionospheric measurement system that is being used to better understand and utilize ionospheric dynamics. GNSS signals are refracted as they travel through the ionosphere to airborne or spaceborne receivers (Coster and Komjathy, 2008; Hickey, 2011). The ionosphere total electron content is continuously measured by multifrequency GNSS receivers to either remove this ionospheric perturbation or to better understand the Earth environment (e.g., Basu et al., 2001; Jakowski et al., 2002; Rideout and Coster, 2006; Kherani et al., 2012). GNSS ionospheric measurements are a significant advancement because they are cost effective and their measurements are multipurposed,

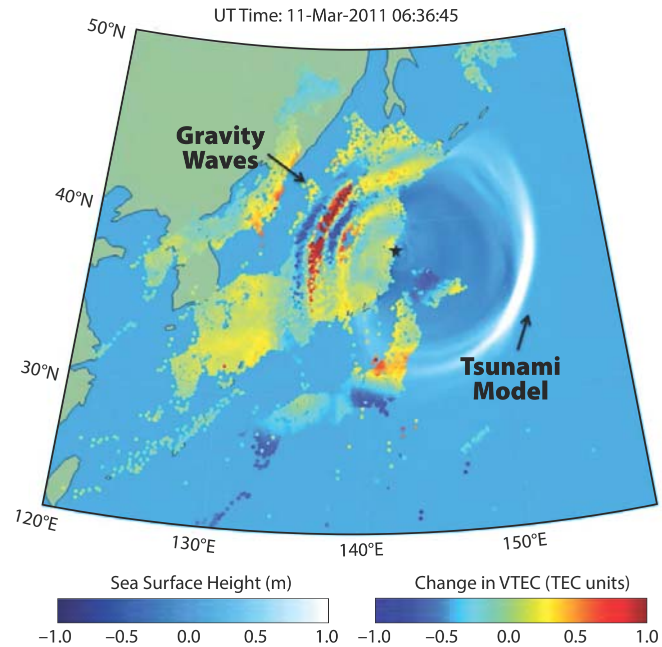


FIGURE SD-10. Ground- and satellite-based instrumentation can observe tsunami-triggered gravity waves in the ionosphere. Shown here are band-pass filtered vertical total electron content maps at ionospheric piercing points above Japan on March 11, 2011, the date of the great Tōhoku earthquake. Each cluster represents locations in the ionosphere where the signal from one GPS satellite, communicating with one ground-based GEONET receiver, passes through the ionosphere at 300 km altitude. The tsunami can be observed propagating away from the epicenter of the Tōhoku earthquake. *From Galvan et al. (2012)*

and because a single GNSS receiver, like a surface radar, can observe the ionosphere over a million square kilometers of Earth's surface.

In the coming decade, multiple constellations of global and regional satellite navigation systems will more than double the number of satellite systems emitting microwave signals in space. The increase in GNSS signals coupled with increases in ground-based and space-based GNSS networks will greatly improve the density of ionospheric piercing points and thereby multiply the spatial resolution of ionospheric observations. Terrestrial network modernization with high-performance, multi-constellation GNSS receiver and antenna systems is required to realize the advantages of the multi-billion dollar international investment in GNSS constellations.

4. Broader Impacts of the NGEO Facilities

The geophysical facilities provided through the NGEO will contribute to issues of national/global strategic importance, including geohazard assessment and disaster resilience; environmental management and economic development; national security; and science, technology, engineering, and mathematics (STEM) education and workforce development. Data and data products from the NGEO facilities will be used by state and federal agencies, including the USGS, National Oceanic and Atmospheric Administration (NOAA), NASA, DOE, and DOD to support mission-agency activities, including earthquake location and characterization, tsunami warning, weather forecasting, water management and environmental monitoring, and nuclear test monitoring. Students trained in the use of these facilities pursue careers not only in academia, but become geoscience professionals in a wide range of fields. NGEO outreach activities promote public engagement and science literary, creating an informed citizenry that can make decisions regarding geoscience-related issues.

Hazards

The NGEO facilities will contribute to community and national disaster resilience by making instrumentation, data, and data products available to researchers, and a wide range of other users, for assessing risks associated with geohazards and as a test bed for research, development, and implementation of new hazard assessment, prediction, and event-warning strategies and technologies.

Earthquakes and Tsunamis. Seismological and geodetic networks are used to quantify stress/strain accumulation along earthquake faults, identify potential seismic hazards, and locate and characterize earthquakes when they occur. For example, the GSN along with the USGS Advanced National Seismic System form the core set of stations used by the USGS National Earthquake Information Center to disseminate information on earthquake location, magnitude, and source mechanism to national and international agencies, scientists, and the general public worldwide. Near-field GPS/GNSS observations show promise for rapid determination of peak ground displacement for more accurate magnitude determination (Melgar et al., 2015a) and tsunami risk assessment (Song, 2007; Blewitt et al., 2009). GPS/GNSS and satellite InSAR measurements are also used to determine the distribution and amplitude of co-seismic and post-seismic fault slip. Inversions of ultra-long-period seismic waves available in real time from GSN stations are used by NOAA's National Tsunami Warning Center to rapidly characterize potential tsunamigenic events, while GNSS-detected ionospheric disturbances show promise as a new tool for tracking tsunami development and propagation (Galvan et al., 2012; **Figure SD-10**).

Induced Seismicity. Recent unprecedented increases in seismicity in some regions of the central United States have been widely attributed to disposal of saline water produced by using enhanced oil and gas recovery techniques in injection wells drilled into deep subsurface geological formations (e.g., van der Elst et al., 2013). The NGEO regional seismic and geodetic networks, as well as campaign-style temporary networks, will provide important space, time, and magnitude statistics of these earthquakes and their relationship to injection wells and stress-strain conditions along fault systems. The improved understanding of the induced earthquake process derived from research using the NGEO facilities can help states and their regulatory agencies implement policies and procedures for successful mitigation of risk associated with induced seismicity (Ellsworth, 2013).

Volcanic Eruptions. Our ability to monitor, forecast, and respond to volcanic eruptions has been greatly advanced through the use of seismic, geodetic, and other geophysical techniques (Tilling, 2008). For example, near-surface geophysical surveys can be used to map shallow volcanic stratigraphy over tens of kilometers, determine the eruption histories of volcanoes, and better assess their long-term hazards. Seismic and geodetic data (GPS/GNSS and InSAR) collected through the NGEO can be used to investigate structures and processes within volcanic systems, including determining the size, shape, orientation, and depth of intrusions (dikes and sills); rates of magma and gas ascent; the volume of erupted magma and gases; and the distribution of seismic and aseismic strain (e.g., Sigmundsson et al., 2010). Once the eruption begins, seismic tremor is a key indicator of the location, intensity, and type of activity, while infrasound data can be used to determine the flux of ash and gases in the atmosphere. Ash clouds, which are important hazards that can disrupt aviation traffic far from the site of the eruption, can also be monitored using satellite and ground-based remote sensing, as well as GPS/GNSS.

Space Weather. Large geomagnetic storms, commonly referred to as "space weather" events, have the capacity to do significant damage to the nation's critical infrastructure, including the electric power grid and aviation; pose a risk to passengers and crew in aircraft; and can make radio communications difficult or nearly impossible. The vulnerability of the national grid to these events has been documented in several reports culminating in the "National Space Weather Action Plan" produced by the National Science and Technology Council (2015). At present, models of the interactions of geomagnetic storms with power grid infrastructure use simple layered conductivity-depth models of the Earth that do not accurately predict current channeling and enhancement of impact due to areas of high conductivity in the subsurface. The "Action Plan" notes the importance of having a complete 3-D model of conductivity across the entire continental United States, which can be obtained with NGEO instrumentation.

Environment, Economy, and National Security

The geodetic, seismic, and other geophysical facilities that will be operated by the NGEO will also contribute in a variety of ways to Earth observations, environmental management, economic development, and national security. Geodetic reference frames are fundamental to Earth observations. A national geodetic reference frame built using space geodesy data provides a uniform and consistent reference platform for imaging and mapping the natural and built environment, managing land use, and comparing geospatial data over time on an Earth that is constantly deforming. The geodetic facilities that will become part of the NGEO include operational support for the NASA Global GPS Network, used by an international community of geodesists along with other data streams, including the PBO, to define and allow consistent access to national, continental, and global reference frames.

Global Water Resources. Water security is one of the central challenges of our time. Tracking all components of water storage (soil moisture, vegetation, surface water, snowpack, groundwater) with remote sensing and ground-based seismic, geodetic, and other data can help forecast crop productivity, flood vulnerability, drought severity, and wildfire risk, and can usefully inform the mitigation of these phenomena. Satellite gravity (GRACE), GPS/GNSS, and InSAR observations of aquifer-related and surface load-related uplift and subsidence are being used to develop a better understanding of these processes and are informing water management policies and associated planning efforts.

Time series of vertical positions of PBO stations have been used to quantify groundwater loss in the western United States during a four-year drought (**Figure SD-7**). GNSS–IR can measure daily snow depth and snow-water equivalent, soil moisture, vegetation index, and water levels. NOAA relies on such geodetic research networks to develop and demonstrate GNSS-based estimates of precipitable water vapor, a critical parameter in the regulation of energy transfer in the atmosphere that is used by NOAA weather models and operational forecasters.

Discovering New Energy Resources. The energy industry, one the world's largest industries, is heavily dependent on geophysical techniques (seismic, geodetic, electromagnetic, gravity) to explore for new energy resources and to monitor and manage energy reservoir production and extraction. Seismological methods, in particular, provide by far the highest resolution information on geological structure and properties in the subsurface and are essential for prospecting for both conventional (oil and gas) and unconventional (e.g., geothermal) energy resources. Industry and academia share many overlapping interests in seismic instrumentation, imaging, and data interpretation, and associated theory and methodologies. The energy industry is also the largest employer of graduates from Earth science programs at U.S. universities, and the training these students receive in use of seismic, geodetic, and other geophysical instrumentation helps prepare them for careers in energy-related fields.

National Security. A number of national and international agencies are dedicated to the work of monitoring signals from nuclear weapon test explosions. Seismological methods are now the principal means for explosion monitoring in the context of achieving two different national security objectives: (1) to characterize the more than 1000 non-U.S. nuclear explosions that have occurred, and events that may occur in the future, as a means for tracking the development of nuclear weapons, and (2) to support nuclear test ban treaties by demonstrating the capability for effective verification. The NGEO facilities will play a major role in the successful achievement of these objectives because of their ability to monitor regions of key interest (e.g., North Korea, Iran) and because of the NGEO's commitment to provide free and open access to data.

Education, Outreach, and Workforce Development

The NGEO is ideally suited to bring cutting-edge science enabled by the facility to a wide audience through its close connection to both the research and education communities, and through its expert staff. The NGEO will support robust education and outreach programs that nurture students along their educational pathways, emphasize reaching diverse student populations, and help create an informed citizenry that can make decisions regarding geophysics-related issues.

Improving STEM Education. High-quality geoscience education is essential as a growing population is exposed to natural and human-caused hazards. The NGEO facilities will enrich students' geoscience knowledge and prepare them for geoscience-related careers in academia, government, or industry.

At the college level, there is a broad movement to improve geoscience education by using instructional practices that are interactive, collaborative, student-centered, and problem- and place-based, that incorporate research and research-like experiences, and that are of relevance to society (NRC, 2009, 2011b). Through the ongoing development of tools such as the GPS Velocity Viewer and the interactive Earthquake Browser, and curricula such as the Bringing Grand Challenges into Classrooms program and InTeGrate, the NGEO will support active learning methods and help position geodesy and seismology in the context of societal challenges.

At the K–12 level, the Next Generation Science Standards (NGSS) (Wysession et al., 2012) have revolutionized science education by developing curricula based upon education research (NRC, 2007, 2008, 2011b, 2013b). NGSS-aligned curricula, in addition to being practice-centered, evidence-based, and data-driven, also require a year of geoscience in high school. There is a tremendous opportunity for the NGEO to be a national leader in K–12 learning by providing (1) hands-on, inquiry-based educational assets such as the Geodetic Education Resources and Seismology in Schools programs, (2) software that builds on existing resources such as jAmaSeis, Visible Earthquakes (via InSAR), Jules Verne Voyager Jr., EarthScope Voyager, and the Rapid Earthquake Viewer, and (3) online and in-person mentoring opportunities and professional development for teachers.

Workforce Development and Broadening Participation. As environmental, energy, and geohazard issues increasingly impact the social, economic, and political health and welfare of the nation, the demands for a larger and more diverse geoscience workforce continue to grow (NRC, 2007; PCAST, 2010). While improvements in formal K–12 STEM education are a vital part of this, particular importance needs to be placed on attracting and retaining underrepresented minorities, so as to produce a more diverse body of geoscience students and scientists (PCAST, 2012; NRC, 2013a). Through summer internship programs, community college partnerships, and professional development activities, many of which successfully target traditionally underrepresented minority undergraduates and graduate students, the NGEO will play an important role in both workforce development and broadening participation in the geosciences (see **sidebar**).

Public Engagement and Science Literacy. IRIS and UNAVCO public outreach programs have long been exemplars of successful informal science education. Engaging geophysical displays have been enjoyed by millions of visitors at leading science centers across the country. These displays have included UNAVCO's GeoHazards exhibits and the IRIS Active Earth Monitors and Earthquake Channel displays. However, by far the fastest growing public audience can be found online through many social media channels, especially those using mobile apps. For example, YouTube animations, videos, and webinars presenting IRIS and UNAVCO content receive over 50,000 views per month with more than 2.5 million cumulative minutes watched. In the NGEO, there will be many new opportunities for additional public and community engagement through social media such as Facebook, Twitter, LinkedIn, Instagram, and Pinterest. The NGEO will also pursue citizen science activities through partnerships with the Quake Catcher Network and the Southern California Earthquake Center.

IRIS Undergraduate Internship Program

Now in its eighteenth year, the IRIS Undergraduate Internship Program has had a significant impact on students' career development and increasing diversity in the geosciences. This program has pioneered a distributed REU (Research Experiences for Undergraduates) model that bonds students into a cohort, and uses cyberinfrastructure to maintain cohesion despite students conducting research at geographically distributed sites (Hubenthal and Judge, 2013). The program has provided 182 undergraduates with the opportunity to work with faculty mentors from 64 different IRIS member institutions. Over 80% of alumni are employed in a geoscience career or are actively pursuing an advanced geoscience degree. Evaluations indicate the program is quite influential in students' career development. For example, nearly 90% of those who have earned a PhD found the program very influential or influential, and the same was true for 80% of those who earned a master's degree. Ongoing efforts to diversify the intern applicant pool have also been successful—over the past four years, 21% of IRIS interns identified themselves as underrepresented minorities. This is up from only 9% during the previous five-year period. Of those employed in the geosciences, careers are split between those in the energy sector (53%) and employment in academia and federal and state governments (44%). Long-term effects on the community are also significant, as program alumni or faculty mentors currently hold nearly a third of the community governance seats of IRIS, several alumni have mentored their own interns, and one is a full-time IRIS employee.

During the 2016 intern orientation week at New Mexico Tech, participants pose with a broadband seismic station they have just installed. The students work together in teams to collect and analyze data during the orientation, both to gain seismology experience and to help build the intern cohort.

5. Proposed Facility Integrated Management and Operations Plan

Geophysical Networks and Portable Instrumentation – WBS 1.1

INTRODUCTION

IRIS's Instrumentation Services directorate proposes to provide a wide range of geophysical instrumentation for the NGEO to meet the needs described in the "Futures" Facility Workshop Report (Aster and Simons, eds., 2015). Foundational facilities essential for research and education include the Global Seismographic Network; a large pool of portable seismic and magnetotelluric instrumentation for use in PI- and community-driven, peer-reviewed experiments; and support for seismic networks and shorter-term seismic experiments in Earth's polar regions.

The geophysical networks and portable instruments operated by IRIS will together be capable of monitoring with high fidelity the spectrum of ground motion from Earth's fundamental normal modes to hundreds of hertz. They will be used to study Earth system processes from Earth's surface to its inner core, and will have the capacity to be deployed rapidly in response to significant geophysical events such earthquakes, volcanic eruptions, landslides, floods, or solar storms. The highly trained professional staff of IRIS and its subawardees will provide users with training, planning, logistics, and field support, as necessary.

The forefront of geophysical research is constantly evolving. New scientific questions stimulate the need for new observing and experimental techniques, which in turn lead to new insights and hypotheses. In coordination with UNAVCO, IRIS will ensure that the NGEO observing capabilities remain state of the art through ongoing interactions with the community of scientists served by the NGEO, and with engineers, technology developers, and vendors regarding NGEO needs, capabilities, and current and future technology. We will also ensure that the NGEO technical staff (IRIS, UNAVCO, and subawardees) exchange technical best practices and information on new technology. A joint IRIS/UNAVCO governance committee, the Instrumentation and Network Services Advisory Committee, will ensure that technological advances in instrumentation and technology are coordinated across the NGEO instrumentation facilities.

In order to support PIs whose science objectives exceed the capabilities of today's instrumentation, we propose to conduct three instrumentation frontier activities, some in collaboration with UNAVCO, that will provide new capabilities for the NGEO in a number of areas, including:

- Establishing the first national, multi-user near-surface geophysics facility
- Acquiring next-generation instrumentation for full wavefield seismic imaging on a variety of spatial scales and for rapid response to geophysical events
- Developing seismic and geodetic instrumentation for making long-term observations on the seafloor in both cross-coastal and remote ocean locations

In the following sections we describe our proposed foundational and frontier instrumentation capabilities, the cutting-edge science they will support, and our vision for how these facility capabilities will evolve over the next 10 years.

DESCRIPTION OF PROPOSED FOUNDATIONAL FACILITIES

Global Seismographic Network (GSN) – WBS 1.1.1

The Global Seismographic Network, with 152 continuously operating stations around the world (**Figure GSN-1**), has set the standard for global, national, and regional seismographic networks since 1988. The GSN is unique for its global breadth, the multidecadal stability of its observations, and the uniform, high-quality, very-broadband, high-dynamic-range continuous data made freely available to all users at no cost and without restriction. Station instrumentation allows high-fidelity recording of signals over a very broad frequency band, from many thousands of seconds to 20 Hz and higher (**Figure GSN-2**). A combination of high-gain (weak motion) and low-gain (strong motion) sensors increases each site's dynamic range. GSN data provide researchers with observations critical for basic research on Earth structure and dynamics and the interactions of the solid and fluid Earth, as well as full fidelity observations of great and moderate earthquakes and

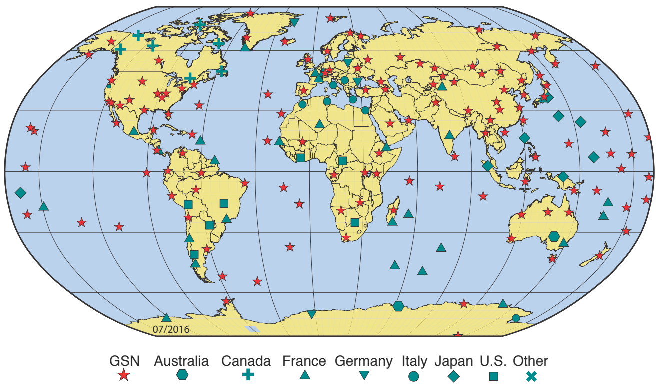


FIGURE GSN-1. Distribution of GSN stations (red stars) and the International Federation of Digital Seismograph Networks (FDSN) backbone stations (green symbols). The GSN avoids duplication of coverage by taking into account the locations of quality FDSN stations. The GSN is jointly operated by IRIS, with funding from the NSF, and the USGS's Albuquerque Seismological Laboratory.

non-earthquake sources. Due to its very broadband recording capability, GSN network data are critical for studies of Earth's normal modes, which help resolve large-scale lateral variations in density and velocity in the mantle and core, and for studies of the largest earthquakes. GSN data are the most requested of all data streams housed at the IRIS DMC.

In 2015, an external review of the GSN was conducted by a distinguished, international group of scientists. This committee was asked to evaluate the present status and operations of the GSN, and to assess strengths, weaknesses, and possible risks to its continuing operations, as well as the potential for improvements and opportunities for growth. The review committee was unambiguous in its assessment of the fundamental importance of the GSN for scientific discovery and earthquake monitoring, as well as mission-agency objectives, stating that: "*The deployment of the Global Seismographic Network (GSN) represents one of the singular achievements of the seismological community during the past thirty years.*" The "Futures" Facility Workshop Report (Aster and Simons, eds., 2015, p. 34) described a long-term global seismographic network like the GSN as "*essential for research on Earth structure, earthquakes, and other topics, and for nuclear treaty verification, and for monitoring, rapid event characterization, and warning systems for earthquakes, tsunamis, and other seismic events.*"

The specific instrumental GSN design goals have been met. As described in the next sections, all GSN stations have three-component sensors and provide observations across a wide frequency spectrum and dynamic range. The spatial coverage goal of placing stations ~20 degrees apart across the entire globe has largely been met on land. GSN stations have additional value as platforms for long-term, telemetered environmental observations. Instrumentation has been added at many stations, including microbarographs (now at most GSN stations), GPS instruments, and geomagnetic transducers, broadening the utility of the GSN to the geoscience community.

Description and Capabilities of the GSN Facility

Figure GSN-1 shows the locations of the 152 GSN stations. Thirty-nine stations (network code II) are operated by UCSD through a subaward from IRIS. Ninety-one stations (IU and IC networks) are operated by the USGS' Albuquerque Seismological Laboratory (ASL). Twenty-two GSN affiliate stations contribute their data to the network, but generally fund their own operations and maintenance. As the GSN was built, the locations of several other high-quality international networks were factored into the siting of GSN stations to maximize global coverage.

The GSN employs a suite of sensors to meet the network's broad frequency band and high dynamic range design goals. The primary (very broadband) seismometers used to capture long period (<0.003 Hz) free oscillations and teleseismic body and surface waves are paired with secondary (broadband) sensors that record high-frequency (>10 Hz) regional signals (**Figure GSN-2**). The spectral coverage of the primary and secondary sensors overlaps, providing a useful level of redundancy should one or the other instrument fail. Strong motion accelerometers complement this pair of sensors to extend the dynamic range of the GSN system. All GSN systems are capable of recording signals as low as local background noise over the frequency band 0.001–20.0 Hz.

GSN stations include other sensors that improve station operations and enhance the utility of the recorded seismic signal. State-of-health transducers provide internal temperature, humidity, and barometric pressure, as well as acquisition-specific metrics (e.g., voltages, mass positions). In addition to the geophysical sensors, infrasound sensors are currently being installed at several GSN stations.

Over the past eight years, the GSN has standardized recording equipment to a design based on the Quanterra Q330HR high-resolution data acquisition system (DAS). This

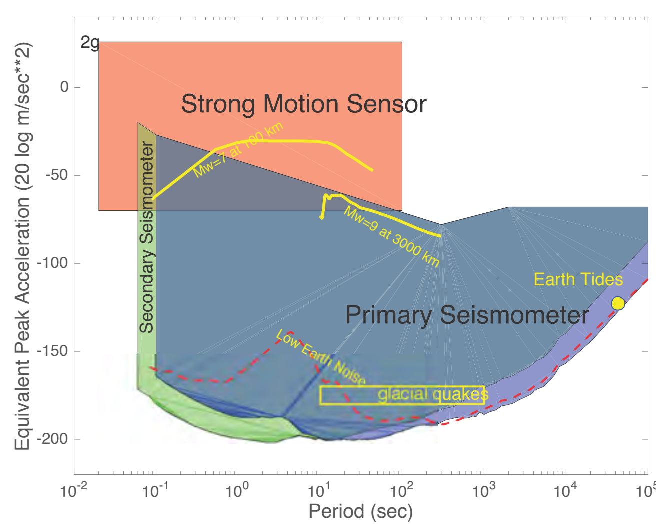


FIGURE GSN-2. The GSN deploys multiple sensors at each station to achieve the design goal of recording many types of signals on scale and with full fidelity. No single sensor can capture all data of interest.

device meets or exceeds specifications developed by the seismological community based on the GSN design goals. The DAS resolves input signals to 26 bits, allows remote calibrations, and operates at low power, which improves operational efficiency and dynamic range. All GSN stations use GPS timing, with disciplined local clocks capable of maintaining timing accuracy in the event of a temporary loss of the GPS signal.

Installation. Considerable effort is made at each GSN site to obtain the lowest noise levels possible under local conditions. To meet geographic distribution requirements, some sites are placed on oceanic islands or in other high noise environments. Most seismometers are installed either in 100 m deep steel-cased boreholes or in vaults tunneled underground. A few vaults are built at the surface or on the foundation of a building. All vault installations have a concrete pier, mechanically isolated from the floor, upon which the seismometers are placed. Many sites are now nearly 30 years old, and the GSN is investing in civil works at several stations to keep them in good condition or make critical repairs.

Telemetry. Data are transmitted over a diverse communications network to reduce costs and increase reliability. Communications costs are lowered by taking advantage of local area networks or host-facilitated long-haul telemetry at over half the stations. A significant number of stations utilize the GCI telemetry operated by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). This topology also minimizes single-point-of-failure telemetry losses that could occur if the telemetry were entirely handled through a single provider. All stations but one (ALE) have circuits with sufficient bandwidth to permit near-real-time retrieval of all data.

Data Quality Control and Distribution. The GSN's goal is to provide the highest possible data quality and dynamic recording range, in support of scientific needs. The IRIS DMC is a crucial link in making GSN station data available to the scientific community. The IRIS DMC maintains the data archive, but also provides easy, rapid, and open access to data recorded from seconds to decades ago. All data flow to the IRIS DMC through the UCSD or ASL Data Collection Centers (DCCs). The DCCs focus on delivering data to the DMC, maintaining correct metadata for GSN stations, reviewing data quality from the stations that the UCSD and the ASL operate, and addressing circumstances that require special data handling, such as back filling following telemetry outages. Key to the high quality of GSN data is the direct feedback on data quality problems identified by the DCC analysts to the network operations staff and field engineers. The near-real-time data that flow to the DMC are seamlessly replaced by a quality-reviewed version as they become available, approximately one day behind real time.

Testing Facilities. The GSN makes routine use of UCSD's extensive seismometer testing facilities on campus and at the Pinyon Flat Observatory (PFO) near Anza, California. The PFO hosts a suite of permanent seismic, geodetic, and infrasonic sensors, as well as facilities for testing new, refurbished, and prototype instrumentation. PFO's Seismic Test Facility is also the location for the permanent GSN station II.PFO, as well as auxiliary vaults, postholes, and boreholes for seismometer testing. The proximity of this test area to the permanent GSN sensors supports straightforward performance assessment of new or repaired equipment. The high level of natural seismic activity in the vicinity of Pinyon Flat also makes this an ideal site to evaluate how well an instrument performs under moderate to strong shaking. For the same reasons, the presence of an operational CTBTO infrasonic array makes the PFO site a desirable place to test infrasound sensor deployment strategies for the GSN. Lastly, UCSD makes use of two shake tables housed in the basement of a building on the campus of Scripps Institution of Oceanography. The instrument response of portable sensors is routinely checked on these tables before and after field deployment.

Research Supported by the GSN

Even after three decades of operation, the GSN continues to provide key data for new and cutting-edge research on earthquake processes, and the structure and dynamics of Earth's interior. The GSN external review committee observed that the range of science produced from the very broadband GSN data is especially impressive, spanning investigations into the fundamental structure and dynamics of Earth's deep interior, the physics of great earthquakes and tsunamis, and unexpected applications such as the seismic signal of landslides and ice-stream processes. The Review Committee found that "*the GSN continually contributes to transformative scientific observations and discovery*," and concluded that the GSN warrants strong continued involvement and support from the NSF and the USGS, and should remain a cornerstone of future seismological facilities.

While earthquakes are a global phenomenon, occurrences of great earthquakes are relatively rare. The GSN has recorded hundreds of moderately large (Mw >7) earthquakes, approximately two dozen great (Mw ≥8) earthquakes, and two giant (M_w ≥9) earthquakes. GSN data play an essential role in understanding these earthquakes and proved especially critical for analysis of the M >9 events in Sumatra in 2004 and in Japan in 2011. The GSN also provides crucial data for understanding earthquakes in regions of poor regional network coverage, such as for the recent devastating earthquakes in Haiti in 2010 and Nepal in 2015.

The GSN's global distribution, high-quality data, and wide frequency band provide the basis for modern research into Earth's elastic and anelastic structure (**Figure GSN-3**). Data constraints from GSN stations allow researchers to obtain remarkably consistent models of global isotropic elastic structure at wavelengths as short as a few thousand kilometers. Investigations into anelastic and anisotropic structure are ongoing and are critical for a robust understanding of mantle dynamics and its potential variability over time. Research into shorter-wavelength structure, where there remains greater disagreement between models, is ongoing.

The GSN's unique capability to record with high fidelity the long- and very-long-period portion of the seismic spectrum is essential for advancing understanding of global Earth structure. This attribute derives from high-quality installations and low-noise siting, as well as use of very-broadband seismometers with excellent low-frequency sensitivity. Very-broadband recording is needed to accurately measure normal mode frequency and attenuation rates, which in turn provide important constraints for better understanding the density (Häfner and Widmer-Schnidrig, 2013), anisotropy (French and Romanowicz, 2014), and anelastic structure (Mäkinen et al., 2014) of the core and lower mantle. Breadth of frequency coverage is also essential for resolving earthquake source properties, including the size and slip history (Bogiatzis and Ishii, 2014) of very large earthquakes, which can have durations of many minutes. Accurate, rapid estimation of earthquake size and focal mechanism for hazard assessment and tsunami warning depends heavily on data recorded at low- and mid-range GSN frequencies (Kanamori and Rivera, 2008).

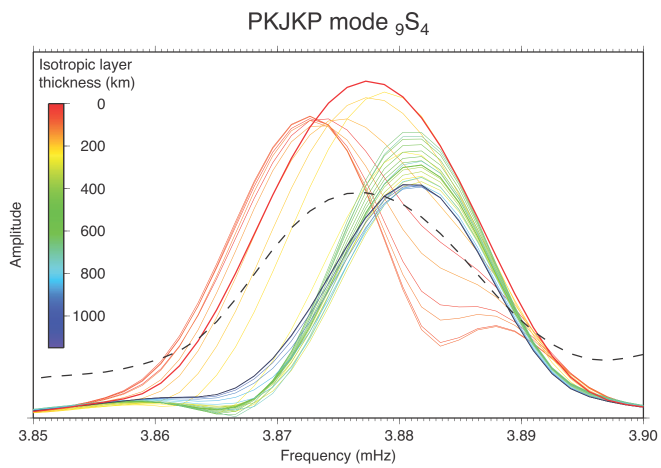
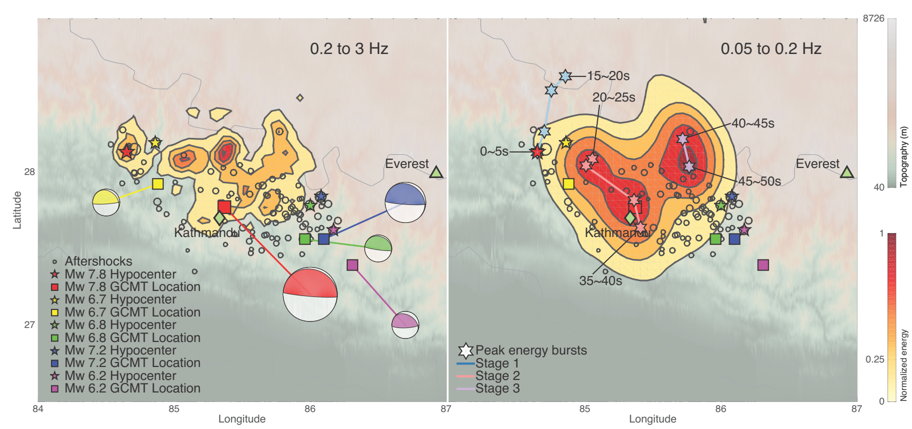


FIGURE GSN-3. The amplitude and attenuation rate of normal modes (Earth's free oscillations) can be used to tease out information about the structure of Earth's core and lower mantle. Comparing recordings (dashed line) of such low-frequency signals, which require GSN primary sensors to capture, enables researchers to test structure models in ways not possible with other seismic data. *From Irving and Deuss (2011)*

The GSN plays a major role in hazard warning by improving the earthquake location resolution and detection threshold capabilities of the USGS National Earthquake Information Center and similar organizations in other countries. GSN stations anchor many national networks, including those in Russia, Indonesia, Iceland, Australia, Fiji, Chile, South Africa, Uganda, UAE, Kazakhstan, Kyrgyzstan, and Pakistan. GSN data streams provide vital information to NOAA and international tsunami warning centers, enabling these agencies to quickly analyze the tsunami-generating potential of an

GSN Data Unravel Fault Slip

During the last decade, the Global Seismographic Network has extensively recorded many very large earthquakes. The global distribution of these high-quality stations has been essential for unraveling the timing and geometry of these events' rupture processes. GSN data are especially important in regions where there are few high-quality seismic stations, and they are key for improving the spatial resolution of back-projection rupture images as compared to those produced from regional arrays of stations. A case in point is the April 25, 2015, M7.8 earthquake that struck central Nepal, killing over 8,000 people. This earthquake occurred on the Main Himalayan Thrust and was the largest event to strike the region since 1934. Using GSN data, UCSD researchers were able to unravel the complex evolution of fault slip during this earthquake. The study concluded that the rupture propagated mostly eastward and occurred in three distinct stages: Stage 1 was weak and slow; Stage 2, near Kathmandu, had the greatest slip but was relatively deficient in high-frequency radiation; and Stage 3 was relatively slow as well. Overall, this earthquake was more complicated, with multi-stage movements on multiple faults, than could be explained by smooth models of continuous rupture on a single fault plane. *From Fan and Shearer (2015)*



earthquake and issue timely warnings to coastal communities. Currently, 50 GSN stations also serve a role as auxiliary seismic stations in the CTBTO's International Monitoring System, which provides data for assessment of Comprehensive Nuclear-Test-Ban Treaty compliance. The GSN has received supplemental funding from the Departments of State, Energy, and Defense to support this aspect of GSN operations.

Plans for the Facility Over the Next 10 Years

The original GSN design goals have largely been met in continental and most ocean island areas. Gaps remain in central Africa and Antarctica and in the southern Indian Ocean, where coverage is dependent on other international networks with which the GSN cooperates. In most oceanic regions, coverage is sparser than needed to resolve deep Earth structure. Recent technological developments put the goal of extending high-quality GSN-like seismic stations into the ocean within reach. Developing the capability for long-term seafloor observations is a proposed NGEO frontier activity (see page 48).

Over the next 10 years, operational efforts will focus on optimizing station performance, maximizing data return, further improving the quality of the data and associated metadata, ensuring the resiliency of the network, and expanding the range of instrumentation supported by the station platforms. Working with the community, IRIS will update GSN design goals as appropriate to reflect new science objectives and to incorporate new technologies.

Optimizing Station Performance. The instrumentation at many GSN stations is over 20 years old, and the original primary sensors (both vault and borehole) are no longer manufactured or supported. The current failure rate of the primary borehole sensors (KS-54000) is now unacceptably high. The next generation of very broadband (VBB) borehole seismometers has been under development over the last few years with Department of Energy funding. Recent testing of prototypes indicates that the sensors are performing well and will meet GSN specifications (**Figure GSN-4**). An initial delivery of these instruments is expected in early 2017. Deployment of these new sensors at the 39 existing GSN borehole sites will begin immediately and is projected to be completed within the first three years of NGEO funding. We expect that as these new sensors replace the obsolete units, the GSN's data return rates will rise beyond its current level of ~91%.

Two-thirds of the GSN stations are housed in conventional vault structures. The primary VBB vault sensor (STS-1) has not been manufactured for several years, and the associated feedback electronics will no longer be supported after March 2019. Functional specifications for a new VBB vault sensor have been developed by a panel external to the GSN and reviewed by the GSN Standing Committee. At this time, a viable prototype VBB vault sensor is not available, but we will continue to work with manufacturers to ensure that a vault sensor replacement is developed.

To improve sensor performance at some vault sites, we will employ new sensor installation strategies. Years of experience operating the GSN and the USArray Transportable Array, along with focused testing of emplacement strategies, show that the vulnerability of a sensor's horizontal components to tilt can be mitigated if the sensor package is buried at even shallow depth (**Figure GSN-5**). At selected vault installations, shallow boreholes will be drilled to accommodate borehole VBB sensor models. The incremental cost of modern VBB instruments over standard broadband sensors is small, and we expect to be able to preserve the GSN's crucial very broad bandwidth while improving noise performance and reliability using this strategy.

Auxiliary geophysical sensors installed as a part of station infrastructure enhance the utility of the seismic data set. We will continue to further diversify geophysical instrumentation at GSN sites by deploying a set of Hyperion infrasound microphones and Vaisala weather stations purchased with current NSF funding. These sensors will be installed at select GSN sites worldwide during visits of opportunity. Joint analysis of seismic and infrasonic data has proven to be useful in detecting volcanic explosive activity before large amounts of volcanic ash and gases are expelled into the atmosphere with the resulting potential dangers to aviation, and in providing important constraints on volcanic eruptive processes. Several GSN stations are currently co-located with, or in close proximity to, permanent continuously operating GPS/GNSS stations operated by UNAVCO or the Russian Academy of

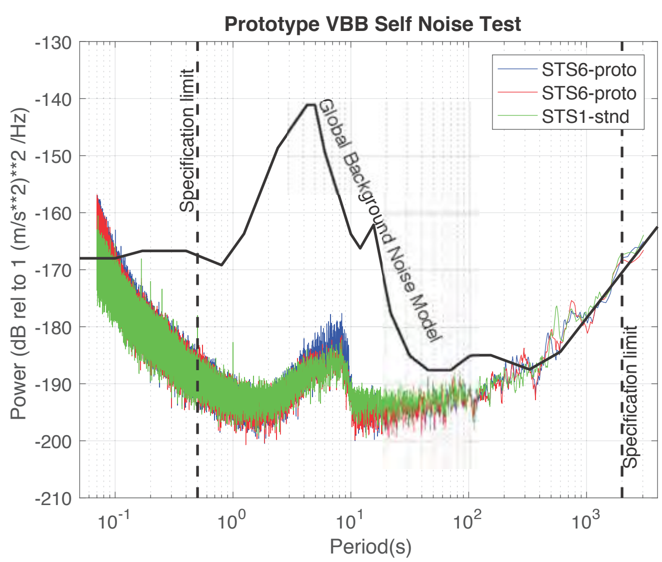


FIGURE GSN-4. Results of performance tests of the new STS-6A very broadband (VBB) borehole sensor prototypes conducted by the USGS. Three instruments (two prototypes and a standard VBB STS-1 vault sensor) are placed in close proximity in an instrument test vault and allowed to record background noise. Plotted here is the remainder of the noise after a signal common to all three sensors is removed. The test shows that the self-noise of the prototypes falls below the lowest noise level (black line) expected globally for much of the required frequency range, whose limits are depicted by vertical dashed lines. *Source: USGS Albuquerque Seismological Laboratory*

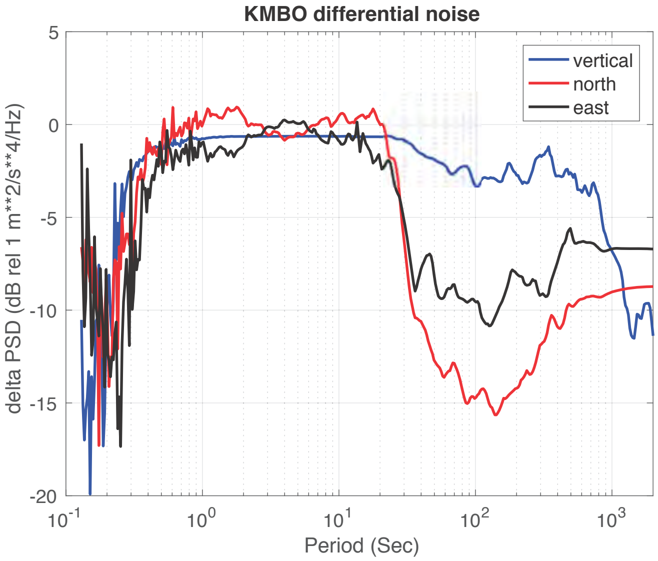


FIGURE GSN-5. Seismic sensor emplacement strategies can be as important as instrument capability in improving overall data quality. This plot shows the difference in noise level (expressed in dB) between the primary VBB STS-1 sensor installed in a vault and a broadband Trillium 120 sensor installed 10 m deep in a nearby posthole at GSN station IU-KMBO, Kenya. Negative values indicate the posthole system is quieter; as expected, the greatest improvement is observed for the horizontal channels. Results of this test support GSN plans to transition some vault installations to shallow boreholes.

Sciences. IRIS and UNAVCO have worked cooperatively to pool operating resources for these sites. We will continue to seek opportunities for increased collaboration in the form of shared infrastructure and telemetry, as well as combined data retrieval of GPS and seismic data streams.

Optimization of Station Distribution. We will continue to evaluate the existing GSN station distribution in light of the current global availability of high-quality digitally recorded VBB stations. The quality of data from many of the regional broadband networks does not meet GSN standards. We will continue to evaluate the suitability of relocating GSN stations from Europe and Japan to regions with sparser coverage, as allowed by available funding. Occasional changes to GSN station locations are necessitated by political instability or the encroachment of local human activity at sites previously remote and seismically quiet. Any alterations to the network configuration and distribution will take into account the GSN's multi-use capabilities for earthquake hazard and nuclear explosion monitoring as well as international partnerships that help support GSN operations.

Maintaining Data Quality. Historically, GSN data quality has been very high, both in absolute terms and compared to other seismic networks. The GSN Review Committee noted that these quality control efforts have "*achieved a level of data quality that is now almost taken for granted by the research and monitoring communities.*" IRIS is engaged with the USGS in efforts to develop new instrumentation technologies and station infrastructure to improve station performance. The application of quality assessment tools developed recently by IRIS and the USGS allow network operators to prioritize maintenance activities and support the community's efforts in setting priorities for the network.

We will continue to analyze, quantify, and improve data quality at all GSN stations. In a coordinated effort, IRIS Data Services is developing general tools that can be applied to all of the data managed at the IRIS DMC, including hundreds of permanent networks and temporary experiments, as well as coordinating quality control with the International Federation of Digital Seismograph Networks (FDSN). Improving GSN data quality, as well as that from other networks archived at the DMC, is viewed as a joint and complementary effort between IRIS's Instrumentation Services (which includes the GSN) and Data Services directorates.

Management and Organization

The GSN is managed and operated as a partnership between IRIS and the USGS. This unique model is a highly effective cooperation that balances mission-agency and scientific needs. The IRIS portion of the GSN program has relied primarily on approximately $2.8M annual funding from the NSF (**Figure GSN-6**). Our USGS partner contributes roughly $4.5M annually for GSN operations through the ASL, an amount roughly proportional to the number of stations operated by that group. The GSN is a highly leveraged facility, with ~$20M in additional funds provided by other federal agencies (including the Departments of State, Energy, and Defense) in the last 10 years. This funding has underwritten the procurement of modern capital equipment and large-scale civil works projects.

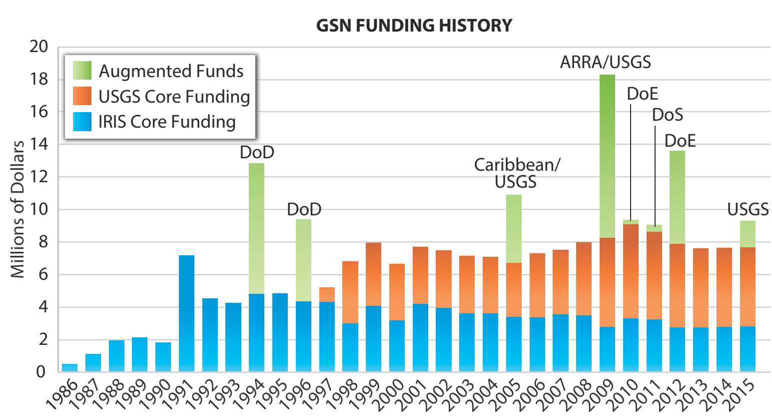


FIGURE GSN-6. Funding history of the GSN showing the leveraging of funds from other entities, especially for equipment modernization efforts. The major augmentations to core IRIS and USGS annual funding are labeled, and total $20.5M over the past 10 years, including supplemental funding from the Departments of State, Energy, and Defense. The cumulative investment in the GSN since its inception is over $200M

The IRIS component of the GSN is overseen by an IRIS Facility Manager. IRIS GSN network operations and the UCSD Data Collection Center are supported through a subaward from IRIS to UCSD's Project IDA (International Deployment of Accelerometers). The IRIS Facility Manager oversees the UCSD operations subaward, and manages the IRIS/GSN program budget and overall plans. The USGS component of the GSN is managed and operated by the USGS' ASL. The IRIS Facility Manager coordinates activities between the two network operators. The GSN Review Committee evaluated this unique structure and found that: "*The utility of having two operators representing academia and government separately offers a distinct operational advantage*," and "*the committee sees no alternative management models that would significantly reduce costs without a negative impact*." An academic network operator embedded at a premier scientific institution like UCSD can establish memoranda of understanding (MOUs) with station partners at international university-based research institutions where a government agency like the USGS could not, while some other MOUs are only possible with government-to-government agency agreements.

In the NGEO, the GSN Standing Committee will advise the GSN Facility Manager, the USGS, and the IRIS Board of Directors on policies and priorities for operation of the GSN. As is current practice, we anticipate that the GSN Standing Committee will continue to be formally recognized by the USGS as the scientific advisory committee for the USGS component of the GSN. Members of the committee will continue to be drawn from IRIS member institutions, federal agencies, and international partners; the committee will include a permanent member of the USGS leadership in an ex officio capacity. The External Review Committee noted that: "*Community oversight and coordinated current activities have turned out to be the most beneficial aspects of the current management arrangement.*" The GSN Standing Committee will report directly to the IRIS Board and to a joint IRIS/UNAVCO Instrumentation and Network Services Advisory Committee. The GSN Standing Committee chair will be an ex officio member of this committee, ensuring that GSN activities are coordinated with other NGEO instrumentation activities.

Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) – WBS 1.1.2

The IRIS PASSCAL facility provides portable instrumentation and expertise to support PI-led and community experiments ranging from high-resolution imaging of subsurface groundwater reservoirs to continent- and mantle-scale investigations of plate tectonic processes. Since its inception in 1984, PASSCAL has evolved well beyond studies of the lithosphere to provide a range of resolving capabilities that tie together the global- and continental-scale fiducial reference networks represented by the GSN and the EarthScope Transportable Array with higher resolution studies of the proposed near-surface geophysics facility. The portable and flexible nature of the PASSCAL facility is critical for studies of seismic source phenomena and rapid response to geohazards. The PASSCAL Instrument Center (PIC) at New Mexico Tech is the heart of the portable facility, with its skilled, experienced staff and instrument pool that serves as a resource for researchers throughout all stages of their experiments.

PASSCAL provides investigators with world-class facilities for conducting geophysical research, regardless of an investigator's career stage or home institution. Data collected from experiments that use the IRIS PASSCAL facility become freely and openly available to all researchers and educators through the IRIS DMC. This democratization of seismology has vastly expanded the research community and diversity of science being conducted using portable seismic techniques, and has enabled over a thousand large- and small-scale experiments throughout the world. The IRIS PASSCAL facility also provides training and curricular (e.g., classroom or field course) support for future seismologists at all career stages, including graduate students and undergraduates, postdocs, pre-tenure faculty, and other early career investigators.

The PASSCAL facility is a critical resource for the U.S. field seismology community as well as a key facilitator of seismic data collection and analysis worldwide. PASSCAL began as a community-driven initiative, and it has developed and maintained an international leadership position in portable seismic instrumentation for over 30 years through a partnership between IRIS management, PIC staff, and the members of scientific community represented within the IRIS governance structure. This partnership has allowed the portable facility to adapt to meet the research and educational community's changing scientific and instrumentation requirements and will ensure that PASSCAL continues to sustain cutting-edge seismological research in the next decade by evolving to meet future needs.

The IRIS PASSCAL program was last reviewed by an external group of international portable seismology experts in 2009. The key overarching finding of the review was summarized in the following statement: "*Although the reputation of the PASSCAL program for excellence had preceded it, this visit served to reinforce this impression in every dimension. PASSCAL has become a model program for how to structure facilities in other areas of the geosciences for good reason. We were pleased to find that the community of Principal Investigators served by PASSCAL are productive and doing cutting-edge science despite either flat or declining budgets across the Geoscience directorate.*"

Description and Capabilities of the PASSCAL Facility

The PASSCAL Instrument Center has been housed at New Mexico Tech since 1998. The PIC maintains the world's largest open access, shared-use pool of portable broadband seismic sensors and associated equipment. It has supported nearly 900 PI-led experiments over the past 16 years (**Figure PS-1**), including passive and controlled source studies in locations ranging from Death Valley to the high Himalayas, and from Antarctica to the lakes of East Africa.

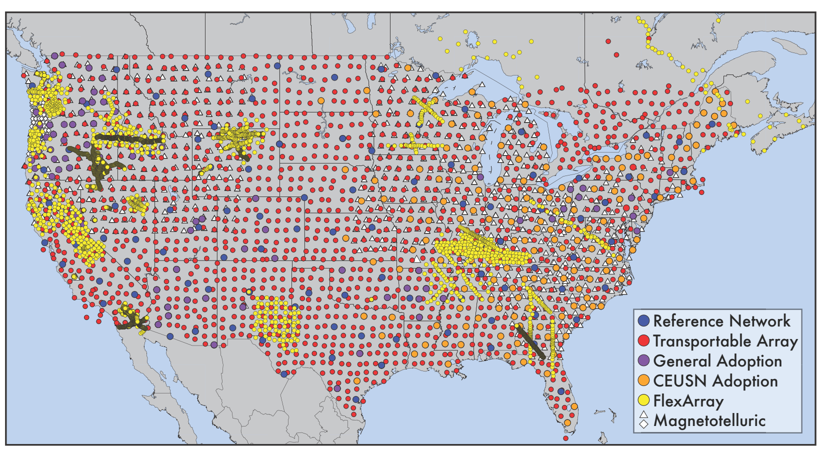
The PIC is a custom-designed facility, built with funds from NMT and the state of New Mexico, that includes over 20,000 ft^2 of office/lab space, ~15,000 ft^2 of warehouse space, and a ~750 ft^2 seismic test vault external to the primary building. Within the lab space, the facility contains multiple areas for bench testing and repair of data acquisition systems and ancillary equipment, as well as a dedicated sensor repair lab. A recent modification to the facility provides a dedicated space for cold-testing equipment, which is critical for the engineering and testing of seismographic systems bound for deployment in polar environments.

Transportable Array – A Unique Capability for the NGEO

The EarthScope Transportable Array (TA) is a large mobile array of 450 high-quality broadband seismographs with real-time telemetry that is designed to image Earth structure, characterize regional seismicity, and study large, distant earthquakes. Beginning in 2004, these seismographs rolled across the lower 48 states from west to east in a continuous field operation, occupying more than 1700 sites with a station spacing of 70 km. After a deployment of two years, each instrument was moved to the next site on the eastern edge of the array. The TA finished its eastward migration in fall 2015, and is currently being moved to Alaska where ~260 stations will be deployed by fall 2017 at ~85 km spacing across the entire state where it will operate for approximately two years. The TA has enabled a broad range of remarkable science, well beyond that envisioned when the project was initiated, including crustal imaging, mantle and deeper Earth structure using both teleseisms and novel approaches such as eikonal tomography from ambient noise (Lin et al., 2009), characterizing regional seismicity (location and size of events) and associated source mechanisms (Astiz et al., 2014; Yang et al., 2014), and studying large distant subduction earthquakes through back projection and array beam forming techniques (Koper et al., 2011; Meng et al., 2011)

The TA is unique in many aspects that distinguish it from PI-driven temporary deployments such as those supported by PASSCAL or permanent global networks like the GSN. The TA can be deployed on a subcontinental or regional scale, it is installed and operated by professional crews working year-round, it provides data in real time, and, as a community experiment, all data are immediately open and available to anyone. The TA provides additional capability through its structured approach to large experiments and its novel approaches to sensor emplacement, power, real-time data transmission, and multisensor integration. Implementing the TA has involved a large-scale system development and engineering effort to meet the challenges of deploying stations in both the continental United States and at remote sites in Alaska accessible only by helicopter. The TA has developed an integrated, streamlined process for station surveying, permitting, construction, and deployment, employing multiple field crews for full-time field operations. The hallmarks of the TA project include innovation, efficiency, multisensor integration, and large-scale deployments for high-quality, large-scale observation. These capabilities remain within IRIS and are available to the NGEO.

A new project comparable to the scale of the EarthScope TA is not being proposed as part of the NGEO. However, major new community-driven projects that could require TA-like capabilities are beginning to emerge from planning within the geosciences community (e.g., the Subduction Zone Observatory [SZO] and the Global Array of Broadband Arrays [GABBA], both of which represent long-term international efforts). Much as EarthScope developed with funding from outside of the core infrastructure support for IRIS and UNAVCO, should funding for new initiatives such as SZO or GABBA develop outside of the NGEO, IRIS retains the technical, logistical, and management expertise to support large national or international community geophysical experiments at a scale far exceeding what individual PIs can achieve, allowing researchers to pursue the exciting scientific opportunities these new initiatives would enable.



The EarthScope Transportable Array consists of 450 high-quality, broadband seismographs with real-time telemetry that, over the course of 10 years, occupied over 1700 individual sites across the United States. The map also shows Magnetotelluric Array and Flexible Array seismometer deployments through 2016 that were supported by IRIS as part of EarthScope. The TA finished operations in the lower 48 states in fall 2015 and is currently being moved to Alaska where ~260 stations will be deployed across the entire state and operated for approximately two years.

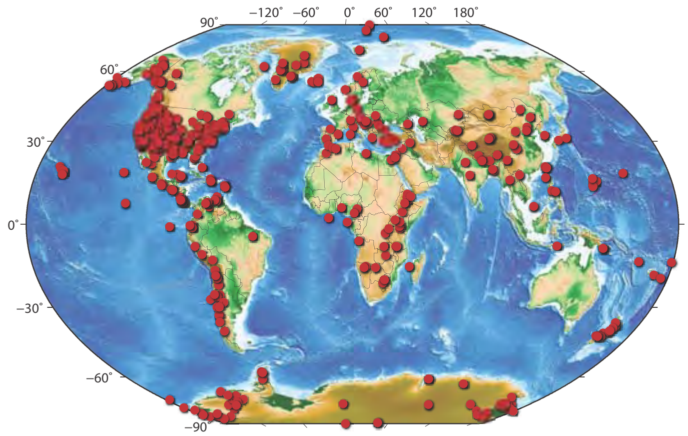


FIGURE PS-1. Map showing location of 888 PASSCAL experiments over the past 16 years (2000–2015). The number of stations for each experiment range from a single instrument to many thousands of sensors.

Over the past decade, the IRIS PASSCAL facility has typically supported 80 to 100 seismic experiments each year, divided about equally between new and continuing deployments (**Figure PS-2**). Given the consistently high level of demand, we expect the need for portable instrumentation services to continue to be strong over the course of the NGEO award.

Instrument Resources

The PIC maintains an extensive instrument inventory and associated infrastructure, as well as expert professional staff that provide services to users. **Table PS-1** provides a current inventory of sensors and data loggers in the IRIS PASSCAL instrument pool. For simplicity, bandwidth can be seen as a proxy for depth of focus: higher frequencies are commonly employed to "see" shallower structures and seismic sources with high resolution, while longer periods can image deeper structures and more distant sources, but with less resolution. These different frequency bands, in turn, are excited by different energy sources. Higher frequencies produced by earthquakes attenuate quickly with distance so artificial "active" or controlled sources are commonly employed to produce nearby seismic energy for smaller-scale imaging studies. The excitation of longer period seismic energy, in turn, requires sufficiently large sources and depends on the "passive" recording of large earthquakes and/or longer-period components of the global seismic noise spectrum generated by Earth's ocean. Methodologies utilizing longer period seismic energy typically require longer (e.g., many months to several years) continuous recording duration, which can increase associated requirements for power, recording capacity, and periodic servicing. All of these trade-offs in bandwidth, resolution, depth, and sources drive the wide range of instrumentation included in the PASSCAL inventory.

In addition to the sensors and data acquisition systems shown in **Table PS-1**, the PIC also supports:

- **Ancillary Systems.** To deploy the equipment described above, the IRIS PASSCAL facility develops and supports a large inventory of ancillary systems, including:
  - Power systems (solar panels, mounting systems, charging systems, etc.)
  - Communications systems (cellular modems, Iridium modems, hand-held terminals, etc.)
  - Power, sensor, and telemetry cabling
- **RAMP Systems.** The RAMP (Rapid Array Mobilization Program) supports a small reserved pool of instrumentation for community use in time-sensitive deployments. Used primarily for earthquake aftershock studies, it has also been used to investigate recent induced seismicity, floods, and glaciological phenomena. In the NGEO, we propose to significantly enhance RAMP instrumentation and support as part of the Next-Generation Geophysical Instrumentation frontier activity (see page 44).
- **Seismic Source Equipment.** Field-deployable sources, ranging from sledgehammers to propelled masses, are provided, typically for use with the cabled geophone systems. Larger sources are typically obtained via explosives, and the PIC provides support for these as well.

Services Provided by the Facility

IRIS PASSCAL staff provide essential services to users of the portable instrument facility that include:

- **Training for PIs and Students.** Hands-on experience with equipment prior to the start of projects allows scientists to effectively utilize the facility irrespective of prior experience or level of institutional resources.
- **Logistics Planning.** Domestic and international projects frequently have complicated implementation plans. Logistical, transportation, field installation, and other expertise at the PIC ensures that deployments are successful.

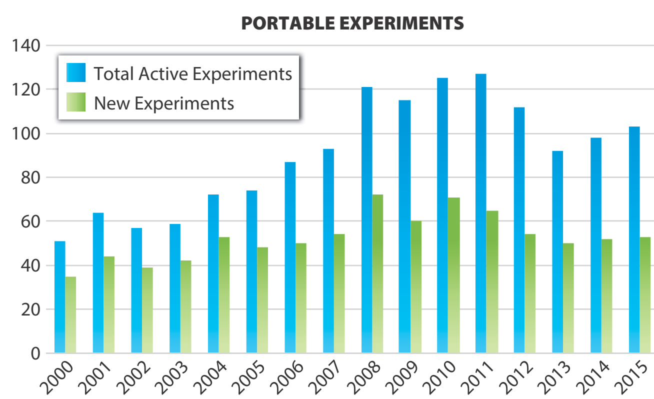


FIGURE PS-2. Number of new experiments and total active experiments each year over the past 16 years (2000–2016). Except for the increase in experiments in 2009–2011 associated with funding provided through the American Recovery and Reinvestment Act of 2009 (ARRA), the PIC typically supports 80–100 experiments per year including 40–50 new experiments.

- **Import/Export/Customs Expertise.** Geopolitical considerations are always present in international experiments. Specialized expertise and experience is required for dealing with complex customs and importation issues. PIC experts provide information and contacts that are essential to the expedient, reliable, and cost-effective delivery and recovery of equipment—following the ever-changing federal regulations and laws.
- **In-Field Training and Support.** Field seismology presents unique challenges, often in addition to those encountered in pre-experiment training at the PIC. In-field training and support by professional staff provide benefits to even the most experienced PIs and facilitates collection of the best data in varied environments. In-field support is also highly beneficial to host participants in both domestic and international projects.
- **Software Development.** In-house developers write and support critical open-source PIC software for essential tasks, including inventory and database maintenance; data handling and archiving; station quality control at lower cost; shorter response time; and higher reliability than commercial or consultant options.
- **General Engineering Support.** PIC staff provide creative engineering and integration solutions for a variety of challenges faced by researchers doing innovative data collection and instrument deployments in challenging field environments. Efforts range from modifications for extreme environments, to adapting power and communication systems, to station and experiment-specific needs.
- **Data Management Support.** All data collected by the PIC become publicly available through IRIS Data Management Center. The PIC staff provides expertise to PIs in validating and converting the various field data formats to archive-ready formats and properly managing data recording parameters (metadata). This is a vital service both to the PI and to the broader community, who benefit from these data in the future.
- **Instrument Quality Control, Maintenance, and Repair.** The PIC tests, repairs, and validates all equipment returned to the facility to assure systems are operational within manufacturer's specifications before they are made available for the next PI. Repair expertise at the PIC has allowed scientists to continue to deploy high-performance seismographic components, such as broadband seismometers, while keeping these instruments within specifications—for upward of 20 years in some cases. This repair capability is especially critical because much of the existing instrument pool was not designed for the rigors to which it is routinely exposed in field seismology.

TABLE PS-1. Sensors and data loggers included in the PASSCAL Instrument Center portable instrument inventory. This table does not include broadband systems used in the EarthScope USArray Transportable Array, which are currently deployed in Alaska.

	PASSCAL	POLAR	RAMP	TOTAL	DESCRIPTION
SENSORS					
Broadband (BB)	802*	124		926	Three-component, 120 sec or more to 25 Hz, low noise, low power, designed for vault deployments. Most versatile, but most delicate and expensive instruments in the pool.
Intermediate (IP)	6	2	10	18	Tens of Hz to tens of secs in high fidelity. Smaller and more rugged than BB.
Short Period (SP)	303			303	1–100 Hz for higher frequency and local source studies.
HIGH FREQUENCY (HF)					
Three-channel	860			860	4.5 Hz and 40 Hz frequencies for crustal and shallow imaging with controlled sources.
One-channel	3231			3231	Geophones (high frequency, single channel) for large active source deployments.
Accelerometer	20		10	30	Rugged and built to withstand large motions from DC to kHz. For strong motions recorded near to large sources.
DATA ACQUISITION SYSTEMS (DAS)					
Three-channel	1234	63		1297	High resolution, high dynamic range, low power for recording BB, IP, SP, and HF sensors in high fidelity. Includes GPS timing.
Six-channel	81	3	10	94	Same as three channel, but can record two separate three-component systems (e.g., BB and strong motion sensors).
One-channel	2600			2600	For recording one-channel geophones at station spacings too large for cabled systems.
Multichannel	17			17	Recorder for cabled systems to be used with geophones for one to tens of meters spacing for very high resolution shallow imaging.
COMBINED SENSOR/DAS SYSTEMS					
Three-component nodes	63			63	Combination of three-channel DAS with HF sensors built in.
All-in-one BB		20		20	Combination of three-channel DAS with BB sensors built in.
All-in-one IP		50		50	Combination of three-channel DAS with IP sensors built in.

* At any given time 650–700 broadband sensors are in the field or available to go into the field.

- **Seismic Source Facility.** The use of explosive sources is currently supported via a subaward to the University of Texas at El Paso (UTEP). IRIS PASSCAL funds UTEP to educate the PI community on the planning and usage of explosive seismic sources and to leverage UTEP expertise. The cost of explosive sources is funded on individual PI grants. IRIS arranges liability coverage for these activities to protect IRIS, NSF, PIs, and UTEP.

Research Supported by the IRIS PASSCAL Facility

The PASSCAL facility supports any Earth science that benefits from recording seismic waves. Unlike the GSN, PASSCAL seismometers can be installed on land anywhere on Earth, and the station density and bandwidth of each deployment can be tailored to suit the specific research needs of each individual project. This flexibility means that PASSCAL serves a tremendously broad range of research, from basic science on plate tectonics, to hazard mitigation and natural resource development.

PASSCAL sensors have been used to image Earth's interior and study dynamic processes over a vast range of scales, allowing us to access otherwise inaccessible information about how our planet works (**Figure PS-3**). PASSCAL passive source broadband deployments have been used to study phase changes in Earth's mantle where a large volume of water, comparable to that of multiple oceans, may be stored (e.g., Liu et al., 2015, Yu et al., 2015). Images from these types of deployments allow us to see the fate of tectonic plates deep inside the planet's interior (e.g., Biryol et al., 2011; Scire et al., 2016), and to see how subduction results in the formation of mountain belts (MacCarthy et al., 2014; Yue et al., 2016) and volcanoes (Waite and Moran, 2009; Heath et al., 2015). By studying the directional dependence of seismic velocities, we can learn much about how the solid mantle "flows" and how this flow affects crustal deformation (e.g., Hammond et al., 2013; Miller and Becker, 2014). PASSCAL instruments and active sources have been used to image fault zones, and have contributed to studies of surface deformation. Increasingly, researchers are combining active and passive source methodologies to study everything from mountain building due to continent-continent collision in Tibet (e.g., Mechie and Kind, 2013), to detailed fault zone structures along the San Andreas (e.g., Hole et al., 2000; Persaud et al., 2016).

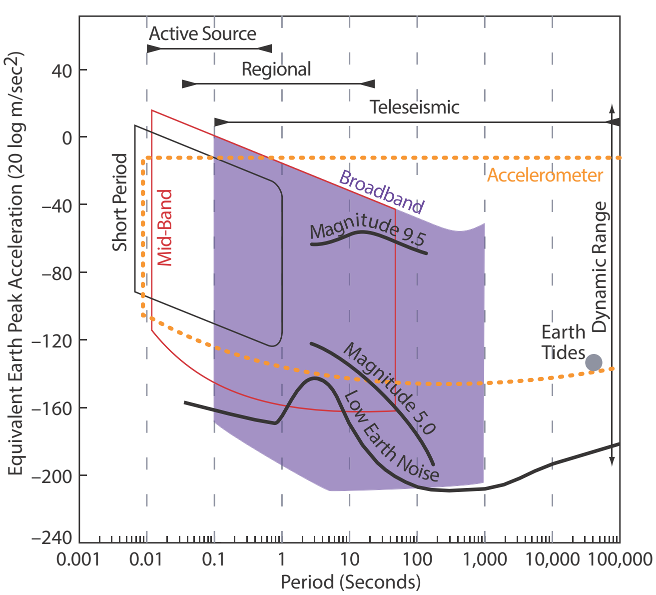


FIGURE PS-3. The wide range of periods (spatial scales) that PASSCAL instruments can support enables studies of Earth structure and dynamics from the inner core to shallow crust.

The flexibility of the PASSCAL pool complements the permanence of the GSN in its ability to study earthquake sources in great detail. In addition to imaging fault structures, PASSCAL instruments have been used to respond rapidly to large earthquakes or those in urban environments (Agurto et al., 2012; Hicks et al., 2014). Studies of episodic tremor and slip, also known as "slow earthquakes," have benefited from the ability of PASSCAL instrumentation to record in remote locations in Costa Rica (Outerbridge et al., 2010) and in Alaska (e.g., Peterson and Christensen, 2009). In addition to earthquakes, PASSCAL instrumentation has been used to study other dynamic Earth processes, including volcanic activity (e.g., Waite et al., 2008; Harrington et al., 2015), debris flows, landslides (e.g., Gomberg et al., 2011), and river bed load transport (e.g., Schmandt et al., 2013), adding to the multidisciplinary toolkit required to study these processes.

IRIS PASSCAL seismographs have been deployed along transects to image high-resolution 2-D profiles of Earth structure and in grids to image 3-D structures (**Figure PS-4**). Relatively recent methodological advances, such as full-wavefield inversions, ambient noise tomography, and scattered wave imaging, allow seismologists to obtain much higher resolution images at greater depth than was previously possible. These approaches have taken advantage of IRIS PASSCAL deployments that have installed broadband stations at as little as 5 km interstation distances (Cascadia; e.g., Rondenay et al., 2001; Bostock et al., 2002), or short period instruments spaced only hundreds to tens of meters apart (e.g., Chaput et al., 2014; Hansen et al., 2015; Kiser et al., 2016).

A new generation of more portable seismic instrumentation is now emerging that is opening up new research opportunities and experimental strategies. A new class of seismographs is being developed that can record with low noise and high fidelity at periods up to tens of seconds. These new "intermediate-period" sensors are smaller, less expensive, and far more robust than the vault-style broadbands of the existing PASSCAL instrument pool. These attributes mean that a scientist can deploy many more stations than previously possible with only a modest increase in cost. This opens up the possibility of hybrid deployments—deployments in which different types of sensors (e.g., broadband and intermediate period) are deployed with different station densities to optimize the

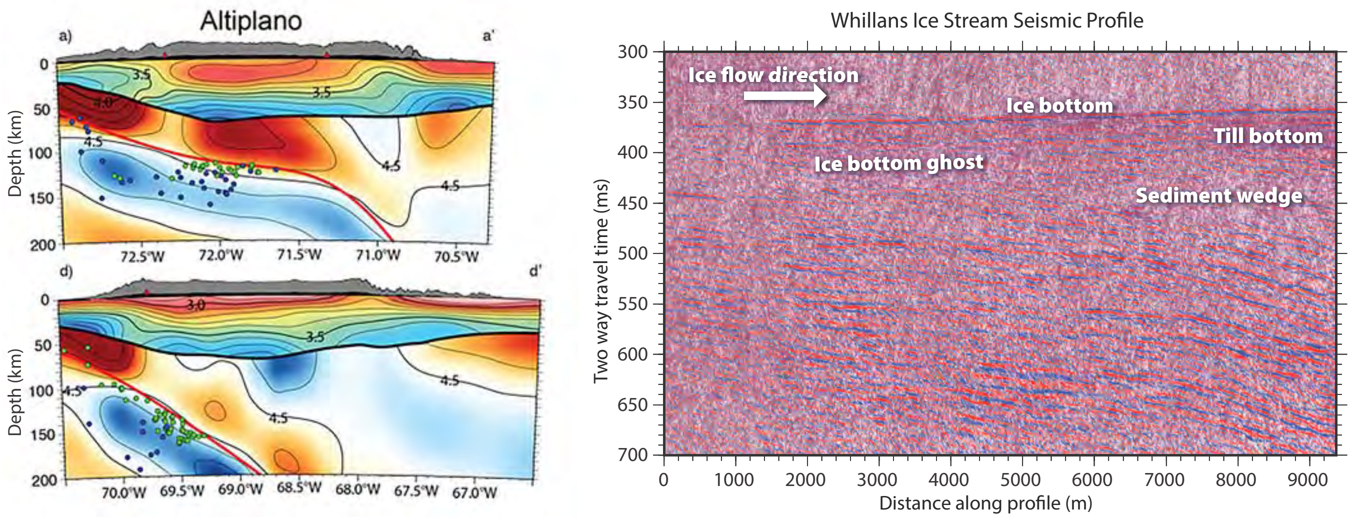


FIGURE PS-4. Examples of broad range of scientific studies supported by PASSCAL facilities. (left) Velocity structure across the Altiplano in west-central South America from ambient noise and earthquake-generated surface wave inversions. *From Ward et al., in review*. (right) High-resolution seismic reflection profile of the Whillans Ice Stream, Antarctica. Ice flow speed is sensitive to hydrological conditions at ice bottom and within underlying till. *From Luthra et al. (2016)* Scale lengths of these studies (~450 km x 200 km in left; 10 km x 1 km in right) indicative of teleseismic to high-frequency bandwidths used in PASSCAL studies.

instrumentation used. Hybrid deployments can also be used to broaden the bandwidth of active source experiments and to blend active and passive source deployments. New instrumentation developed for the exploration industry ("nodes" or "nodal sensors") record three components at frequencies as low as 5 Hz. These sensors can record continuously for a month or longer, and can be used to record both shots and natural seismicity. Nodes can be used in conjunction with broadband seismographs to achieve higher resolution than would be feasible with the seismographs alone, while still allowing for the additional bandwidth and depth resolution provided by broadband seismographs.

These new sensors and deployment strategies are already beginning to be employed. Current and next generation equipment were used to image the San Jacinto Fault (Roux et al., 2016), and to produce high-resolution 4-D images of the 2011 Virginia earthquake sequence (Davenport et al., 2015). In addition, hybrid deployments of broadband and high-frequency instruments are now being deployed to observe seismic wavefields with the most efficient number of instruments (e.g., iMUSH array, Sweetwater array, IRIS Wavefield Community Experiment).

Plans for the Facility Over the Next 10 Years

Informed by community input to the "Futures" Facility Workshop Report (Aster and Simons, eds., 2015), we will focus on the following priorities for the IRIS PASSCAL facility in the NGEO:

- Maintain and sustain the existing instruments, infrastructure, and services to allow continued support of community portable seismological experiments—optimizing techniques for deployment and operations to assure experiment success while minimizing maintenance costs.
- Begin the process of evolving the composition of the instrument pool through the addition of modern instrumentation, including both nodal sensors and intermediate-period seismographs, to support cutting-edge scientific research, including full wavefield imaging.
- Expand the level of services provided by the Seismic Source Facility to make it accessible to a larger user base.

Sustaining Capabilities. The highest priority at the start of the NGEO is to continue to support current capabilities. Our efforts will focus on the maintenance, testing, and evaluation of the pool equipment, and continued training of the community on best practices for installations that will assure high-quality data return and the longest possible life cycle for all of the equipment. Throughout the time frame of the NGEO, we expect several sensors, DASs, and subsystems to become obsolete and unsupported by vendors. We will use this situation as an opportunity to evolve the facility over the next decade, incorporating new technologies to meet the changing needs of the science community that the PASSCAL facility supports.

Renewal and Evolution of the Instrument Pool. The needs of cutting-edge research continually push the capabilities of the existing instrument pool to obtain ever-improved resolution of Earth structure. Our facility plan for the next 10 years will incorporate recent advances in sensor technologies and hybrid deployments and data analysis strategies to meet the demanding requirements of tomorrow's seismic imaging experiments. This will require investment in instrumentation that is currently underrepresented in our current pool. Over the time period of the NGEO award, we will evolve the seismic portable instrument pool to include:

- **Broadband Sensors.** We anticipate that the number of vault-type broadband sensors in the PASSCAL instrument pool will decrease during the first 10 years of the NGEO due to attrition. These sensors will be replaced by newer, more robust, posthole seismometers. We anticipate incorporating into the PASSCAL pool many of the 200 such sensors that are currently deployed as part of the Transportable Array in Alaska. We will monitor the evolving usage of broadband instrumentation, as the introduction of intermediate-period sensors may alleviate some of the demand for broadbands. If this is the case, it may not be necessary to replace the entire broadband vault-style pool with the newer posthole broadband sensors. This would result in a smaller, but more robust and likely less maintenance-heavy broadband instrument pool by the end of the first 10 years of the NGEO (an inventory of ~670 broadbands compared to ~800 broadband sensors today; see **Figure PS-5**).
- **Intermediate-Period Sensors.** Newly available intermediate-period sensors can record data with low noise and high fidelity from many tens of Hertz to tens of seconds, a period band that is particularly useful for newer imaging techniques such as ambient noise tomography and scattered wave imaging. These intermediate-period sensors are smaller and less expensive, and their posthole design makes them easier to deploy and more robust than the broadband systems commonly used today. The ease of deployment makes these sensors ideal for source studies in remote or challenging areas. As a frontier activity, we propose to enhance the current pool with 380–400 additional intermediate-period systems by the end of the first 10 years of the NGEO and will target external funding to further enhance this capability. Substantial procurement of intermediate-period sensors will begin during Year 4 of the NGEO (**Figure PS-5**).

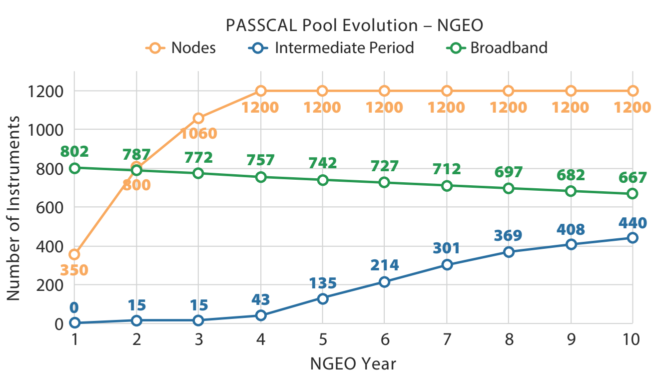


Figure PS-5. Planned evolution of the PASSCAL instrument pool over the 10 years of the NGEO. PASSCAL will take advantage of advances in seismic instrumentation to add intermediate-period and nodal sensors to the instrument pool, while gradually decreasing the number of full broadband instruments. This will give the facility the flexibility to support the specific needs of investigators, including hybrid deployments that use sensors that are optimally matched to the signal frequencies and wavelengths of interest, allowing full wavefield imaging at a wide variety of different spatial scales.

- **Nodal Systems.** The "nodal" sensors developed for use by the energy industry record three components of ground motion with a natural frequency of ~5 Hz within a small and completely self-contained unit. Each unit includes the sensor, data acquisition system, timing, and power. They can record continuously for a month or longer without battery replacement or recharge, and can record both controlled sources and earthquakes or other natural sources of seismic energy. These instruments will replace the current single channel "Texan" pool and will expand the capabilities of the current pool, allowing substantially longer recording times and reducing operational and logistics costs. Lease options for experiments requiring significant numbers of these instruments minimize long-term facility maintenance costs. We have gained experience with these instruments over the last year and propose acquiring larger numbers in the first few years of the NGEO with a goal of having ~1,000 nodes available at the PIC within the first five years of the NGEO. Additional node systems (~200) will be acquired for use in rapid response systems (**Figure PS-5**).

This phased approach to transforming the composition of the portable instrument pool is closely tied to the Next-Generation Geophysical Instrumentation frontier activity described in this proposal (see page 44). It provides flexibility to respond to scientific developments and an ability to mitigate unexpected performance issues with particular instrument types. This strategy will also allow us to take advantage of the emerging technological developments in seismic sensors and recording systems over the next decade.

Seismic Source Facility. Complementing changes in the composition of the instrument pool, we plan to change the implementation of the Seismic Source Facility in the NGEO. UTEP, through a subaward from IRIS, will continue to provide seismic source field support for PIs; however, we propose to fund explosive source work as a supplemental cost to the IRIS NGEO award rather than as direct cost to a PI grant. This will improve the controlled source facility in a number of ways:

- Relieve the burden on the PI of directly contracting for explosive source services, enabling both experienced and novice users of explosive sources to realize the benefits of the same expertise.
- Task IRIS Management and Governance to provide oversight of the source facility (through the Portable Geophysical Instrumentation Standing Committee), as it currently does with all other IRIS PASSCAL activities.

Management and Organization

The PASSCAL Instrument Center will be operated and managed through a subaward to New Mexico Tech. The NMT PI and PIC Director will work closely with the IRIS PASSCAL Facility Manager on the overall management of the facility while the responsibility for day-to-day PIC operations, support and personnel resides with the PIC Director and NMT PI. **Figure PS-6** shows the PIC management structure.

Community input on the technical capabilities and operation of the PASSCAL Facility will be provided by the joint IRIS/UNAVCO Portable Geophysical Instrumentation Standing Committee and the Instrumentation and Network Services Advisory Committee.

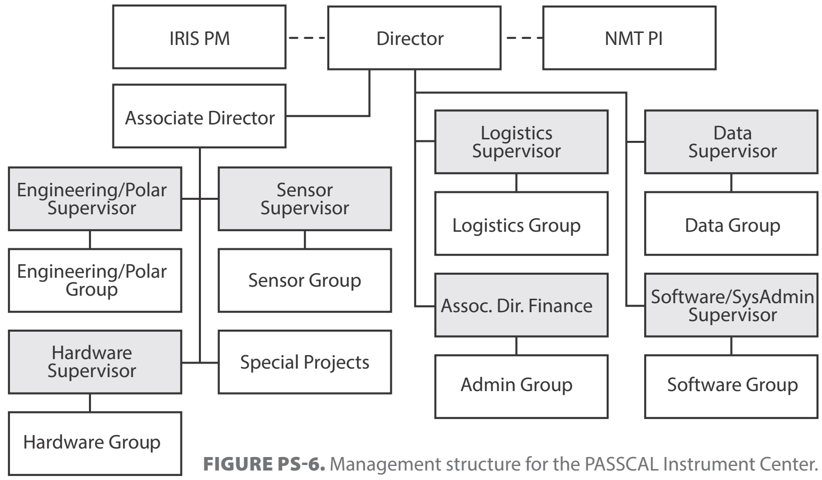


FIGURE PS-6. Management structure for the PASSCAL Instrument Center.

PASSCAL Polar Support Facility – WBS 1.1.3

Supporting portable and long-term seismological experiments in the high-latitude regions of the world requires specialized engineering and logistics expertise applied to standard instrumentation to ensure that these challenging and costly installations provide high-quality data return (Aster and Simons, eds., 2015). Within the PASSCAL Instrument Center, IRIS has assembled a structure and team that leverages personnel and facilities of the PIC and provides the needed expertise to provide state-of-the-art solutions for PIs working in polar regions (**Figure PL-1**).

Polar and glaciological studies have advanced dramatically in the past decade in response to growing awareness and interest in the past, present, and future of the coupled solid Earth-ocean-cryosphere-climate system. While the IRIS PASSCAL program has supported polar experiments for over 25 years, it is only in the last 10 years (**Figure PL-2**) that the NSF has provided incremental and supplemental funding to facilitate engineering and other developments sufficient to realize routine high-quality, short- and long-duration seismic observations in harsh polar environments. During this period, IRIS has provided specific engineering support and has worked with vendors to design, develop, integrate, test, and deploy unique state-of-the-art seismological observatories designed for remote autonomous operations. This effort serves as a catalyst for engineering solutions for station design extending across all of IRIS's Instrumentation Services. In addition, IRIS has developed a facility that promotes opportunities to share designs, facilitate discussion and interchange, and provide training and field expertise across the broader polar research community. To realize this, IRIS has worked with UNAVCO and scientists from a wide range of disciplines to exchange advances through scientific and technical workshops, as well as open sharing of engineering designs through our Web page.

Description and Capabilities of the PASSCAL Polar Support Facility

The IRIS Polar Support Facility is integrated with, and leverages, the infrastructure and general management, administrative, logistics (warehouse, shipping/receiving, import/export), and technical support related to sensor testing and repair, hardware and software development, and data handling within the PIC. The IRIS Polar Support Facility coordinates with the UNAVCO Polar Facility, both in technical interchange and field operations—allowing optimized design and operations of seismic and geodetic polar observatories (which are jointly utilized in many PI projects). Specialized IRIS polar support and design efforts, accomplished independently and in conjunction with UNAVCO and the vendor communities, have produced robust, polar-specific instrumentation systems that now facilitate 24/7/365 recording and telemetry of geophysical data from the most remote and extreme polar environments on Earth. Our sustained research and development effort has led to vastly improved reliability and ease of deployment for power systems, enclosures, telemetry, and deployment strategies, and has cultivated unique vendor community ties to produce continued improvements in cold-rated sensing and acquisition systems. The IRIS polar-specific pool of instruments currently includes 66 cold-rated data

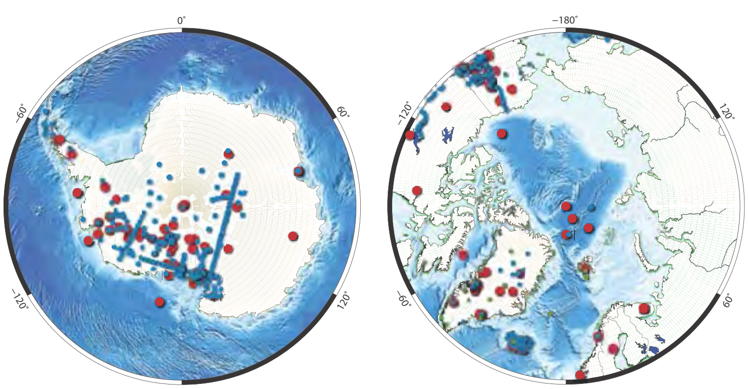


FIGURE PL-1. Locations of experiment centroids (red), individual PASSCAL stations (blue), and Greenland Ice Sheet Monitoring Network (GLISN) stations (green) where IRIS provided Antarctic and Arctic experiment support.

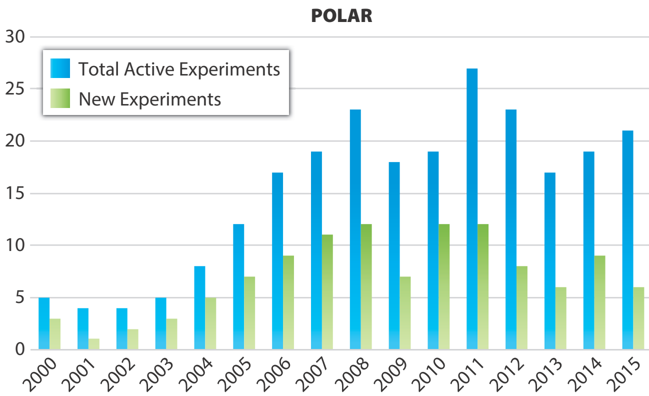


FIGURE PL-2. Polar experiment support from 2000 to 2015. Over the past 15 years, the number and variety of seismic experiments IRIS supports in polar regions has grown dramatically.

acquisition systems and 126 broadband sensors. IRIS is also the steward of approximately 70 broadband and intermediate-period cold-rated sensor/DAS systems through a partnership with Central Washington University that are available for general community use. In addition, we maintain a stockpile of low-power, high-latitude, low-temperature-capable Iridium telemetry systems (capable of state-of-health or full data telemetry), specialized enclosures, and cold/cold-dark power systems (see **Table PS-1**). The IRIS Polar Support Facility continues to highly leverage the PASSCAL seismic portable pool, as much of this equipment can be used to facilitate science during summer or in "moderate" (e.g., temperate mountain glacier) environments.

The Polar Support Facility depends on a dedicated polar engineering group with unique experience and training, as well as on core PASSCAL staff. Ongoing responsibilities include basic support and readiness of the specialized instrument pool (including instrument evaluation, repair, testing, and general maintenance). Polar Support Facility staff also support specialized research, development, integration, and testing of novel engineering solutions to realize high-quality seismic data collection in varied polar environments. This work focuses on station robustness, data quality, logistical ease, and optimization (smaller, lighter, faster to install, etc.), including full integration, assessment, and cold testing of instruments to assure field worthiness. IRIS has procured multiple cold testing chambers and, with its partners at New Mexico Tech, has created a specialized cold testing facility at the PIC that permits realistic component and system testing to temperatures of −70ºC (**Figure PL-3**) to ensure successful experiments. PIC staff provide uniquely qualified assistance to PIs on experiment planning, field logistics and procedures, and instrument training (remote and on site).

Research Supported by the Polar Support Facility

As science activities have accelerated in polar and other glaciated regions, IRIS and UNAVCO have worked across glaciological, seismological, geodetic, and other user communities in coordination with the NSF to develop a long-range facility plan for sustained support of seismic and geodetic observations in polar environments (Nyblade et al., 2012). This plan articulates science motivations and requirements from the community for facility capabilities. Key research targets associated with both the seismological and geodetic communities may be grouped into three basic fields:

Ice Mass Balance and Sea Level. Sea level rise from enhanced ice sheet discharge (including ablation, melt, and dynamic losses) is one of the largest and most immediate consequences of climate warming. Sea level change over the last century due to thermal expansion of the ocean, enhanced river discharge, reservoir impoundment, diminishing glaciers, permafrost, and aquifer pumping has led to a net global sea level increase of 1.7 ± 0.5 mm/yr (IPCC, 2007). The rate of sea level rise increased to 3.1 ± 0.7 mm/yr in the past decade, and is projected to increase to ~4 mm/yr by 2090 under current emissions scenarios (IPCC, 2007).

Observations of glacial thinning, retreat, and acceleration are detected geodetically and seismically along most glaciers with negative mass balances, but the detailed mechanisms triggering these changes are not well known. In several cases, changes in glacier flow dynamics are a response to climate-related perturbations at the seaward margin, although other mechanisms related to changes in subglacial hydrology might also play a role in speed increases. Obtaining a better understanding of sea level change requires improved ice sheet-ocean-atmospheric models and observations of both seismic and geodetic phenomena.

Crustal Structure, Tectonics, and Ice Sheet Stability. Polar continental regions represent important elements of the global plate tectonic system and contain cratonic cores that have been a part of this system since the Archean. Antarctica and Greenland are also climatologically key regions where Earth's major ice sheets are affected by both ongoing geodynamic processes and inherited tectonic features. These

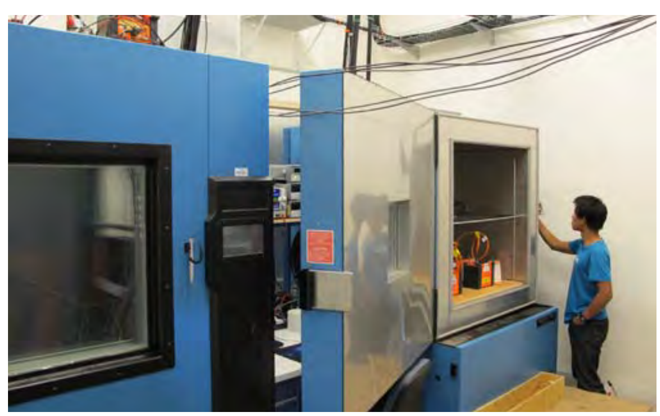


FIGURE PL-3. Cold chambers in a specialized room at the PASSCAL Instrument Center allow testing of components and systems in expected field environmental conditions.

processes determine the topography, heat flow, and hydrology that control the evolution of polar glacial and meteorological systems through recent Earth history.

Modeling seismic and GPS observations collected at remote stations on Greenland and on Antarctica draws on a rich array of methods developed initially for other continents. These methods are central for determining present structures and processes and for inferring the past and future evolution of these key polar continental regions, including their ice caps. Data collected by a network of seismographs deployed with the assistance of IRIS during the International Polar Year (2007–2009), and that are still in operation, revealed that the elevation of the sub-ice cap Gamburtsev Mountains is supported by a buoyant, thick crust as opposed to the mantle, indicating the mountains predate Cenozoic glaciation, forming a key part of Antarctica's paleogeography for hundreds of millions of years (Hansen et al., 2010; Lloyd et al., 2013). Conversely, in West Antarctica, similarly supported experiments have for the first time mapped out the details of thin crust and warm, altered mantle underlying the West Antarctic Rift System, including the magmatically active subaerial volcanoes of Marie Byrd Land (Lough et al., 2013; Chaput et al., 2014; Heeszel et al., 2016).

Deep Earth Structure and Processes. Seismic instrumentation in polar regions facilitates studies of the deep planetary interior that have previously been precluded by sparse station coverage at high latitudes. One example is inner core structure, for which polar recordings are crucial due to the approximate alignment of the fast axis of inner core seismic anisotropy with Earth's spin axis (e.g., Sun and Song, 2002). Seismic energy that travels through the deep Earth, particularly PKIKP (or PKPdf) phases recorded in Antarctica, often show large travel time anomalies due to inner core anisotropy. In this case, the anomalously fast PKIKP arrival times can be fit by a structure in which 3% polar-aligned anisotropy occurs in the outermost inner core beneath southern Africa. Continued networks of seismographs in polar regions will allow these and other variations in deep Earth structure to be mapped out and studied in much greater detail than is currently possible.

Plans for the Facility Over the Next 10 Years

Polar climates and associated glaciological, oceanic, and atmospheric systems are quickly changing. To ensure that peer-reviewed, decadal-scale science advances, the Polar Support Facility engineering expertise and general assistance must keep pace with both technological developments and changing science needs, developing wholly new capabilities to support observational networks in some of Earth's harshest environments, just as they have for the past 10 years.

Advancing Polar Support Facility capabilities will require continuity of polar engineering excellence, coupled with continued availability and development of robust, flexibly configurable, and effectively/efficiently deployable instrumentation. Over the next 10 years, we propose to enhance geophysical observational capabilities in the following areas:

- "Permanent," fully telemetered seismographic and GPS/GNSS stations that can be deployed in even the harshest environments for up to five years between field visits
- Systems engineered for high-accumulation/ablation/melt regions
- Glacial, ice shelf, and iceberg systems that require continuously changing sensor orientation and location metadata.
- Autonomously networked, high-frequency and potentially drone-deployable instrument systems (e.g., low-cost nodes) for high-hazard or other polar targets
- Facilitated integration of additional data types (e.g., infrasound or meteorology)

In addition to these enhancements, as IRIS incorporates near-surface geophysical facilities as a frontier activity, we anticipate the polar and near-surface instrumentation users and facility elements will share instrumentation needs, solutions, and expertise to enhance both communities where interests overlap (e.g., thawing polar permafrost systems or the critical glacial bed environment).

Management and Organization

Management of the PASSCAL Polar Support Facility will be the responsibility of the IRIS PASSCAL Facility Manager, with staff assistance from an IRIS Project Associate. Polar projects will continue to be supported by the PASSCAL Instrument Center through a subaward to New Mexico Tech to leverage general PASSCAL management, governance, instrument pool, staff expertise, and infrastructure. Organizationally, the Polar Support Facility will reside within the PIC engineering group and will be supervised by the lead engineer and director (see **Figure PS-6**).

NGEO community input on the technical capabilities and operation of the Polar Support Facility will be provided by the joint IRIS/UNAVCO Polar Networks and Instrumentation Standing Committee and the Instrumentation and Network Services Advisory Committee. This governance structure will ensure the staff/community communications and interactions required for the facility to continue to advance the research needs and aspirations of the seismological, glaciological, and other polar science communities.

PASSCAL Magnetotelluric Facility – WBS 1.1.4

Magnetotelluric (MT) studies record Earth's ambient electric and magnetic fields to produce conductivity models of the crust and mantle comparable in resolution to seismic imaging methods. Conductivity is a complementary physical property to seismic velocity and is particularly sensitive to the presence of fluids. Joint analysis of co-located seismic and MT data sets greatly improve the ability to determine the structure of the crust and mantle (e.g., McGary et al., 2014). To support these investigations of the continental lithosphere, IRIS proposes to establish a national, multi-user MT instrumentation pool at the PIC. This IRIS facility will be a resource for current and future MT investigators, bringing MT capabilities into the mainstream, and leveraging PIC expertise to facilitate new multidisciplinary geophysical investigations. These MT facility plans are in direct response to a recommendation in the "Futures" Facility Workshop Report (Aster and Simons, eds., 2015; p. 36) that "*future facilities should include centralized and maintained access to 100 long-period and wideband MT systems to support PI-led campaigns.*"

The EarthScope USArray MT community data set, collected by Oregon State University (OSU), has exposed many investigators to MT techniques and data. However, support for PIs to conduct their own MT experiments has been a relatively small part of the USArray MT activity, thus limiting potential for growth in the number and variety of experiments and users of MT techniques. In the NGEO, we will establish an environment where MT will flourish, using the same practices that have made the PASSCAL seismological program so successful.

Description and Capabilities of the Magnetotelluric Facility

Initially, the PASSCAL MT facility will utilize MT resources (**Figure MT-1**) developed under the EarthScope USArray MT program to support PIs in NSF-funded, PI-driven experiments. IRIS manages this existing capability through a subaward to OSU, who operates a depot of MT systems. As the NGEO proceeds, the existing obsolete instruments from the USArray MT program will be replaced with modern, more capable instruments, and the MT depot capability will transition to the PIC at New Mexico Tech to provide PIs with seamless, standardized tools and support across both seismological and magnetotelluric capabilities.

IRIS will procure new commercial-off-the-shelf (COTS) long-period systems with the goal of growing the MT instrument pool into a significantly larger and more diversified community resource than it is today. The existing instrument pool consists of 27 portable long-period Narod Intelligent Magnetotelluric Systems (NIMS) and one LEMI-417 long-period MT system. **Table MT-1** shows the instruments that will be available at the beginning of the NGEO award. The NIMS are no longer manufactured and will be replaced using an open, competitive procurement process, with careful validation and testing to ensure that the new instruments will meet all community performance objectives.

The MT operational model in the NGEO will transition from the present EarthScope program where MT data are collected by USArray staff as part of a community experiment to a PI-driven model, like PASSCAL, in which the facility primarily supports individual PI and larger community-funded experiments. A PI scheduling database will be employed with maintenance and logistics tracking systems—all part of the current PASSCAL capability. Links between U.S. MT practitioners and a robust overseas MT community are strong and, in many cases, collaborations have been essential to gain access to equipment and capabilities not available domestically. We will continue to support international collaborations and sharing of MT instrumentation and expertise.

Facility capabilities will include testing, repair, storage, staging, shipping/receiving of MT systems, training PIs on best practices for deployments, and assisting with fieldwork and data handling as needed. Deployments of MT instruments typically last several weeks, and the facility will initially have the capacity for at least one large deployment (15–20 systems) at any given time. Eventually, this will grow to three deployments. Software resources will be furnished to PIs for quality control, processing, and production of time-series data and data products for archiving at the IRIS DMC, with guidance available to PIs during this process. The facility will leverage several IRIS-related forums to promote the use of MT capabilities, including short courses, Research Experiences for Undergraduates (REU) opportunities, and webinars. Through both the PIC and its community activities, IRIS will create an atmosphere for the natural

FIGURE MT-1. The current fleet of community magnetotelluric (MT) systems, including three-component magnetometers (left) and receivers and electrodes (right), is sufficiently portable, but aging. New instruments will result in a more robust capacity for portable, PI-led surveys.

TABLE MT-1. Current inventory of MT systems.

INSTRUMENT	COUNT
NIMS transportable MT system	21
NIMS transportable MT system (converted from Backbone type)	6
LEMI-417 MT system	1
PbCl electrode pairs	~70

connection between seismic, MT, and near-surface geophysical investigators. With IRIS-facilitated OBSIP activities, we will be ideally situated to pursue cross-shoreline and marine MT collaborations.

Research Supported by the Magnetotelluric Facility

The MT facility will support PI-driven experiments funded through a diverse set of NSF programs. Electrical conductivity, the physical property measured by MT, provides a unique constraint on various Earth processes, especially those involving fluids. MT surveys can directly contribute to constraining the rheology of the crust and mantle (e.g., Jones et al., 2013), mapping the distribution and circulation of fluids and volatiles in Earth's interior (both aqueous fluids and partial melt), particularly in subduction settings (e.g., Soyer and Unsworth, 2006; Wannamaker et al., 2009; Worzewski et al., 2010; Heise et al., 2012; McGary et al., 2014; Evans et al., 2014), and understanding the structure and evolution of the lithosphere and underlying asthenosphere (e.g., Meqbel et al., 2014; Bedrosian and Feucht, 2014; Sarafian et al., 2015) (**Figure MT-2**). An emergent area where electromagnetic (EM) methods can play a critical role is in understanding the role fluids play in generating seismicity. MT instrumentation in the NGEO can contribute to cross-shore surveys of subduction zones or passive margins.

The constraints provided by EM methods are most powerful when viewed in combination with those from other geoscience disciplines. This includes a parallel analysis of conductivity with seismic properties (e.g., Jones et al., 2013), as well as incorporation of geochemical and laboratory constraints into a systems view of target areas. Although joint inversion of seismic and MT data is an emerging field, the use of seismic constraints to guide and improve MT models is well documented (e.g., McGary et al., 2014). Electromagnetic studies also provide unique and valuable constraints for assessing the vulnerability of power infrastructure to space weather.

Plans for the Facility Over the Next 10 Years

The MT facility will evolve over the first half of the award, transitioning from the current facility at OSU to become part of the PIC. This consolidation reduces the overhead of operating two similar facilities, makes efficient use of the larger, longer-term PASSCAL facility to broaden access to MT instruments, and facilitates joint seismic/MT experiment support. IRIS will ensure a smooth transition with minimal impact on continuing experiment support. Early on, OSU staff will focus on transmitting technical lessons learned from the operation of EarthScope MT-TA stations to the staff at the PIC. This will be done through a series of site visits and joint tasks, such as developing equipment training and field support programs. Initially, a small number of EarthScope NIMS and related equipment will be transferred to the PIC for training both staff and PIs. The PIC will serve as the primary point of contact for equipment requests and shipments. The MT systems will be available alongside the PIC's inventory of seismometers to encourage cross-disciplinary studies. Following the model of seismic equipment loans, no insurance or user fees will be charged to U.S. PIs.

IRIS will conduct one or more competitive procurements to add approximately 100 long-period and 40 wideband MT systems during the span of the award. Long-period MT provides similar resolution to many traditional lithosphere-scale seismic imaging methods. Wideband MT systems are sensitive to crustal-scale structures and will bridge the capabilities of the Near Surface Geophysics Facility and the long-period MT instrument pool. Our goal is to replace and exceed the current capacity of the existing NIMS systems by Year 3 of the award, to reach a new level of long-period MT capability and establish some wideband capability by Year 7, and have a full inventory of wideband systems by the end of the award. The procurement process will entail communication with vendors through requests for information and the purchase of pilot instruments for test and evaluation, proceeding quickly but deliberately toward larger procurements.

In addition, IRIS will create a community resource of open, shared MT data processing software tools. The tools will enable the PIC to support PIs with quality-controlled time-series data for archiving at the IRIS DMC. In addition, this software will produce MT Transfer Functions (MTTFs),

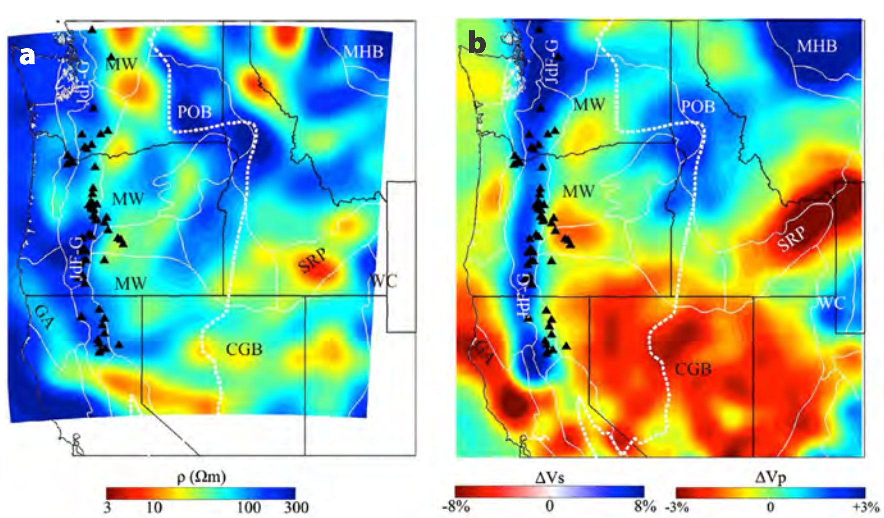


FIGURE MT-2. Joint seismic and electromagnetic studies have proven particularly useful in understanding the structure and evolution of the lithosphere and underlying asthenosphere. Comparison of (left) conductivity model at 100 km depth (Bedrosian and Feucht, 2014) to (right) P-wave velocity model at 90 km depth (Schmandt and Humphreys, 2010). Key features in common include the Juan de Fuca-Gorda Plate (JdF-G) variability in the mantle wedge (MW) above the subducting slab and magmatism in the Snake River Plain (SRP).

a standard data product used in MT analyses. Like time-series data, MTTFs will be freely and openly available to the broad community after the optional two-year data embargo for PI data sets. With IRIS Data Services, we will explore the potential automation of MTTF processing as a web service, available to PIs for all archived continuous MT data.

IRIS will broaden recognition, accessibility, and collaboration for MT science. IRIS and PIC staff will promote these capabilities through short courses and information sessions at NGEO-related workshops and other large Earth science meetings during Years 2-6, including the biennial and internationally focused Electromagnetic Induction of the Earth Workshop. We will sponsor a community science workshop in Year 6. MT practitioners will be engaged for data processing short courses and REU sponsorship. IRIS management and governance will ensure coordination with facility staff supporting shallow EM-related geophysics proposed under the Near-Surface Geophysics Facility.

Management and Organization

MT facility activities will be supported through subawards to OSU and NMT. During the first two years, there will be a transition from OSU to the PIC; however, the PIC will oversee day-to-day activities. The current IRIS MT Facility Manager will oversee the transition of the MT facility from OSU to NMT and associated subawards, equipment procurements, budgeting, and reporting. After the transition is complete, the IRIS PASSCAL Facility Manager will assume responsibility for the MT facility at the PIC.

The transition between subawards will be carefully structured and paced. Goals for technical interchange, software development, and acquisition of new instruments will be clearly articulated and closely managed by IRIS. When the NGEO award begins, we will have in place a working group of stakeholders composed of management and technical staff from IRIS, the PIC, and OSU, to oversee the progress of various elements of the transition. This group will meet regularly (virtually) to measure progress against milestones set out in the formal transition plan. It will also seek guidance with members of the MT community as needed. There is some specific risk in the recapitalization of instruments. The selection of COTS hardware may be relatively limited and from small vendors, thus requiring extra time for selection, testing, and delivery. As a result, OSU will continue to maintain the NIMS and leverage their reserve of instruments until new instruments are fully integrated at the PIC.

NGEO community input on the technical capabilities and operation of the MT facility will be provided by the Portable Geophysical Instrumentation Standing Committee and the Instrumentation and Network Services Advisory Committee. Input from the MT community will be especially valuable for this nascent program. As this will be a program in transition, we will assess the performance of the program and adapt, as necessary, to ensure that community needs are being met. Once the facility has fully transitioned to the PIC, we will conduct an independent community-led review of this facility to provide feedback and guidance to ensure an appropriate level of service to the MT community.

DESCRIPTION OF PROPOSED FRONTIER FACILITIES

Near-Surface Geophysics Facility (NSGF) – WBS 1.1.5

We propose to create the first national, multi-user Near-Surface Geophysics Facility (NSGF), to be managed by IRIS and located at the University of Wyoming. This frontier facility fills a national gap in geophysical instrumentation, as noted in the "Futures" Facility Workshop Report (Aster and Simons, eds., 2015), and will serve community research needs in areas such as critical zone science, hydrology, geomorphology, soil science, natural hazards, engineering geophysics, biogeophysics, and food/water security. The NSGF will engage a diverse user base, connect the NGEO facility to a broad range of interdisciplinary science, and create new opportunities for education and outreach.

Scientific Need

Many processes critical to human societies, ecosystems, and landscape evolution occur at or just beneath Earth's surface, including groundwater recharge, soil erosion, agriculture, and natural hazards such as landslides, floods, and fires. Near-surface systems are subject to increasing stress from a changing climate and increased human development. There is an urgent need to improve understanding of near-surface systems as they encompass complex integrated physical, chemical, and biological processes. Fundamental advances in understanding these systems will result from improved characterization of the subsurface environment through near-surface geophysics (**Figure NSG-1**).

Although the field of near-surface geophysics is currently experiencing rapid growth and an increasing breadth of applications, the Earth science community lacks a national facility for access to near-surface geophysical instrumentation. While some specialists will always require dedicated instrumentation in their own labs, many researchers and students across the geosciences lack access to the geophysical equipment, software, and training that would advance their education, teaching, and research. This access gap is a barrier to answering fundamental questions about the near subsurface in several fields:

- **Critical Zone Science.** Geophysical surveys (Parsekian et al., 2015) have begun to elucidate deep critical zone processes (St. Clair et al., 2015; **Figure NSG-2**), but future advances require investment in a larger campaign of drilling and geophysical measurements (Riebe and Chorover, 2014).
- **Water Security.** Near-surface geophysics can provide critical information about subsurface aquifers at the catchment

scale (Robinson et al., 2008); snow water equivalent, snowmelt, and snow redistribution processes (Marchand and Killingtveit, 2005; Holbrook et al., 2016); and contaminant transport and remediation (Atekwana and Atekwana, 2010).

- **Hydrology.** Applications of near-surface geophysics to hydrological science continue to expand, at scales from pores (rock physics and hydrogeophysics), to biome (ecohydrology), to watershed (Binley et al., 2015).
- **Biogeophysics.** Biogeochemical processes are critically important to soils (Chorover et al., 2007), weathering, and critical zone activity (Buss et al., 2008), as well as to remediation of contaminants in groundwater (Flores Orozco et al., 2011). In recent years, geophysical properties have been linked to biofilms, microbial growth, and microbially mediated redox reactions and mineral transformations (Atekwana and Slater, 2009). These findings open the door to field-scale geophysical imaging of a range of microbial processes (Williams et al., 2009).
- **Food/Energy/Water Nexus.** Near-surface geophysics provides key information on all three corners of the food-water-energy nexus, in applications ranging from precision agriculture (Grote et al., 2003) to the impacts of wastewater produced during energy production (Lipinski et al., 2008).
- **Natural Hazards.** Surface and near-surface processes occasionally have devastating and tragic consequences, such as the 2014 Oso, Washington, landslide that killed 43 people. Near-surface geophysical measurements are broadly used to quantify and characterize natural hazards, including landslides (Wilkinson et al., 2016), sinkholes (van Schoor, 2002), earthquakes (Hole et al., 2006), and volcanic eruptions (Courtland et al., 2013).
- **Cryosphere.** Near-surface geophysical techniques, including ground-penetrating radar, and electromagnetic and seismic methods, are widely used to quantify changes in Earth's cryosphere, including permafrost, continental glaciers, and snowfields (Hubbard et al., 2013). While some instrumentation needs for cryosphere research are unique, we expect that some crossover needs will be met by a national NSGF.
- **Engineering Geophysics.** Near-surface geophysics has wide engineering applications, including appraisal of dam and levee stability, depth to bedrock for construction and earthquake codes, and highway and runway assessment (McDowell et al., 2002). These applications have direct connections to workforce development in geotechnical fields.
- **Homeland Security.** Near-surface geophysics provides capabilities critical to national security, such as detection of land mines and unexploded ordinances, nuclear tests, and tunnels (Pringle et al., 2012).

A recent online survey to gauge interest in an NSGF garnered more than 200 responses from students and researchers across diverse disciplines. The results demonstrate strong demand for access to near-surface geophysical instrumentation (**Table NSG-1**).

Frontier Challenge

The frontier challenge is to establish the first multi-user, national facility for near-surface geophysics. Our vision for the NSGF is to catalyze a paradigm shift in understanding near-surface Earth processes by empowering researchers, students, and educators to accurately measure variations in the physical properties of Earth's shallow subsurface over multiple scales. The mission of the NSGF is to: (1) provide broad access to state-of-the-art near-surface geophysical instrumentation for research and education; (2) provide training, education, access to software, and data analysis support to users; (3) contribute to, and expand on, IRIS's

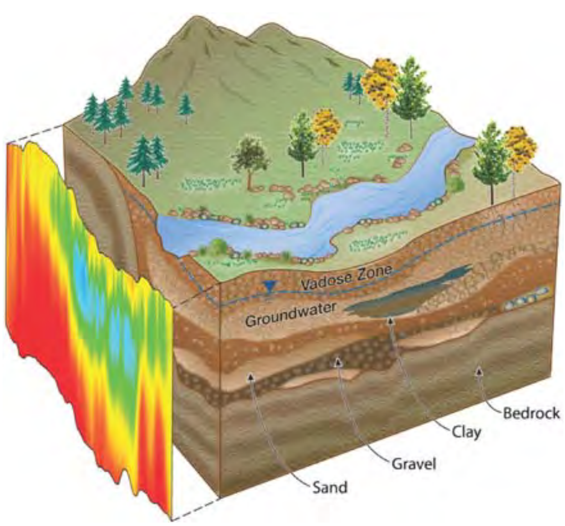


FIGURE NSG-1. Cartoon showing conceptual model of the subsurface in a watershed and the use of near-surface geophysics to infer variations in subsurface properties like porosity. *From Binley et al. (2015)*

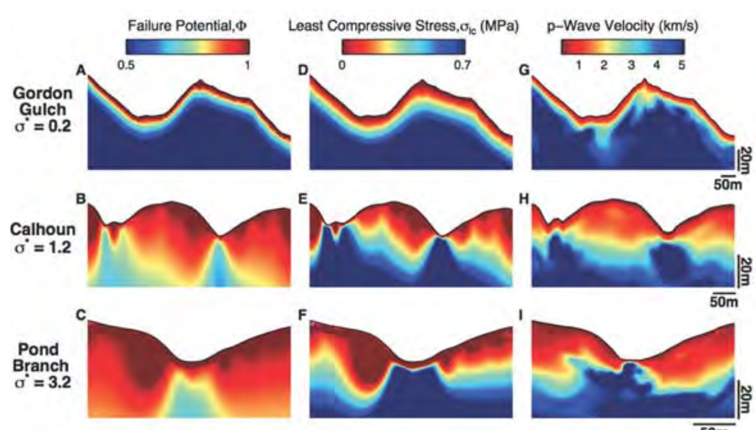


FIGURE NSG-2. Near-surface geophysical studies suggest that both regional and topographic stresses affect porosity (and thus water storage potential) in the critical zone. Results show seismic P-wave velocity (right column) at three locations across the continental United States, compared to two measures of failure potential (left and center columns) calculated from 3-D stress models. *From St. Clair et al. (2015)*

TABLE NSG-1. Online survey results. Expected demand for near-surface geophysical instrumentation, according to number of individual responses (out of 206 total) to frequency and duration of use of different instrument types.

	FREQUENCY OF USE			DURATION OF USE			
METHOD	SEVERAL TIMES/ YEAR	ONCE/ YEAR	ONCE/ SEVERAL YEARS	A FEW DAYS	1 WEEK	2 WEEKS	>2 WEEKS
Seismic refraction	35	53	50	23	49	52	17
DC electrical resistivity/IP	50	43	48	25	56	43	23
Ground-penetrating radar	45	58	50	23	62	44	22
Nuclear magnetic resonance	7	21	42	30	33	25	8
Magnetotellurics	7	20	46	42	30	20	9
Time-domain electromagnetics	21	33	48	31	44	33	8
Magnetics	20	19	40	31	36	30	8
Gravity	13	29	45	32	39	27	15
Electromagnetic induction	22	36	58	34	46	28	9
Borehole logging	23	41	47	26	43	32	15
Drilling & sampling	44	45	43	19	48	37	24
GPS	87	33	26	15	36	52	38

efforts in workforce development through increased access to near-surface geophysical instrumentation and training; (4) maintain and upgrade instrumentation to ensure a modern and efficient facility; and (5) develop and follow "best practices" in facility management, user support, financial responsibility, and responsiveness to community needs.

Description and Capabilities of the NSGF

Locating the NSGF at the University Wyoming will leverage a five-year, $20 million EPSCoR grant by the NSF to the UWyo and a $4 million investment by the university to establish the Wyoming Center for Environmental Hydrology and Geophysics. The UWyo will provide the university-owned near-surface geophysical and associated instrumentation acquired for the Center for use by the NSGF, providing a cost-effective way to jump start this facility and provide this new capability to the Earth sciences community. This instrumentation, purchased in 2012 at a cost of ~$2.6 million, is in excellent condition and spans a comprehensive suite of electrical, electromagnetic, potential field, and seismic methods (**Table NSG-2**). The NSGF will also have primary use of an existing UWyo building. This 7000 sq ft building is currently occupied by the Wyoming Center for Environmental Hydrology and Geophysics' near-surface geophysics facility and is well suited to staging geophysical operations.

While the current UWyo facility provides an excellent starting point for a NSGF, the community survey suggests that user demand will exceed existing instrument capacity. We therefore propose to acquire additional instrumentation in Years 1 ($500K) and 6 ($250K) of the NGEO. While we anticipate critical needs in several instrument types (e.g., ground-penetrating radar, electromagnetic induction, resistivity, magnetics, and transient electromagnetics), decisions about instrument acquisition will be based on community input and use data from the first several years of facility.

TABLE NSG-2. Existing instrumentation at the University of Wyoming that will be made part of the NSGF. As noted in the text, an addition $750K will be invested in NSGF instrumentation in Years 1 and 6 of the NGEO.

METHOD	INSTRUMENT	NO.
Seismic refraction	Geodes (24-channel)	10
DC electrical resistivity/ induced polarization	Supersting (56-electrode)	4
	MPT (64-electrode)	2
	Powersting	1
Ground-penetrating radar	Mala (100, 250, 500, 800 MHz)	2
	S&S Noggin (100, 250, 500 MHz)	1
Nuclear magnetic resonance	Vista Clara GMR	1
Controlled-source audio magnetotellurics	Geometrics Stratagem	1
Time-domain electromagnetics	ABEM WalkTEM	1
Magnetics	Geometrics G-858 gradiometer	1
	G-856 base station	2
Gravity	Scintrex CG-5	1
Electromagnetic induction ("soil conductivity meter")	Geophex GEM-2	1
	DualEM 1-S	1
Borehole logging	Mount Sopris suite	1
	Vista Clara Javelin	1
Drilling & sampling	Geoprobe 7822DT	1
GPS	Trimble handhelds GeoXH	3
	Trimble R8 base	1

Instrumentation. The NSGF will provide access to a suite of near-surface geophysical instrumentation that spans a range of methods, including subsurface sampling and logging.

The equipment will be kept in good working order through regular maintenance, and pre- and post-deployment checks, and will be upgraded occasionally as new technologies are developed. There is no overlap in instrumentation between the PIC and the NSGF, except for a small number of Geode seismic recorders at both facilities that are used for seismic reflection/refraction studies. The NSGF and PIC will coordinate the use of these instruments as necessary. As the facility evolves and the types of usage become clear, the NSGF and the PIC will assess, in consultation with the community, the need for Geodes at both locations and shift the PIC Geodes to UWyo if warranted.

Experiment Support. The NSGF will support field surveys by: (1) maintaining a fair, transparent, and efficient scheduling system; (2) offering advice on survey design; (3) coordinating shipping to and from field sites; (4) providing on-site field technician(s) for instruments that require highly trained operators; and (5) providing call-in support from users in the field. There are no geographical limitations on equipment use, so we anticipate supporting surveys anywhere in the world. The NSGF will follow similar procedures for borrowing instruments to those used by PASSCAL. Any research or educational institution may request the use of equipment for research or educational purposes. The schedule will be determined in the fall of each year for the following year. Projects funded by the NSF Division of Earth Sciences will have the highest priority followed by projects with funding from other NSF divisions, the State of Wyoming, or other U.S. government or state agencies. Unfunded projects will be supported on an "instrument available" basis.

Training, Software, and Data Services. We anticipate users from diverse disciplines who may not have expertise in acquisition and analysis of near-surface geophysical data. Therefore, the facility will train users (through short courses, workshops, and on-site instrument instruction) and provide access to software. Expert consultants supported through the facility grant will provide data analysis advice to users. Access to all data acquired with NSGF instrumentation will be open according to NSF policies and will be permanently archived at the IRIS DMC.

Management and Organization

The NSGF will be operated through a subaward from IRIS to the University of Wyoming, similar to the way in which the PASSCAL Instrument Center is operated under a subaward from IRIS to New Mexico Tech. An IRIS Facility Manager will oversee this award, coordinate activities of the NSGF with other IRIS instrumentation facilities, and receive community input from the Near-Surface Geophysics Standing Committee. The UWyo will be responsible for ensuring the facility is run in a responsive, transparent, efficient, and financially responsible manner. The Facility Director at UWyo will be responsible for the day-to-day operation of the NSGF, including supervising the NSGF technical and administrative staff, scheduling experiments and other instrument use, tracking instrument maintenance and repairs, providing instrument and technical support to facility users, and ensuring data collected by the facility is submitted to the IRIS DMC. The NSGF plans to use processes and software for scheduling, inventory management, and repair tracking that have been developed and employed successfully at the PIC for many years. Close coordination between the NSGF and the PIC is anticipated on many fronts.

The NSGF Facility Director will be primarily supported on a state line at the University of Wyoming. The NSGF staff will include two geophysical technicians (MS or PhD-level) and one administrative assistant/accountant. Both technicians will conduct instrument check-in/check-out and maintenance, user training, and user support. One technician will have primary responsibility and expertise in on-site and remote user support, while the second technician will have primary responsibility for data handling and transfer to the IRIS DMC. The NSGF will hire one full-time graduate student and three part-time undergraduates to help with training, instrument packing/shipping, instrument check-in/check-out, data handling/uploading, and user support.

Community oversight will be provided by the Portable Geophysical Instrumentation Standing Committee, which will include members of the diverse near-surface geophysics community. This will facilitate good communication and coordination between the NSGF and the PASSCAL and MT facilities, which will also be represented on this governance committee. Because this new facility will be supporting a wide range of instruments and methods with a diverse user base, including non-experts who may be using a geophysical method for the first time, in the early years of the NSGF we anticipate establishing a Near-Surface Geophysics Working Group to provide advice and guidance on the establishment and operation of this new national facility. An independent, community-led external review of the NSGF will held in Year 4 of the NGEO to assess the performance of this new facility and identify future needs and areas for improvement.

Next-Generation Geophysical Instrumentation – WBS 1.1.6

The scientific community served by the NGEO requires state-of-the-art observing systems to stay at the cutting edge of geoscience research. In this frontier activity, IRIS and UNAVCO will evaluate, test, and acquire emerging and future geophysical systems and capabilities motivated by community needs defined in the "Futures" Facility Workshop Report (Aster and Simons, eds., 2015). In particular, next-generation geophysical instrumentation will be acquired in three areas:

1. State-of-the-art instrumentation capable of full wavefield seismic imaging, including nodal sensors and intermediate frequency posthole seismic sensor systems that can be

deployed at high numbers and at spatially unaliased densities to much higher wavenumbers than has been possible in the recent past.
2. Geohazard rapid response capabilities (e.g., natural or induced earthquake aftershocks or swarms, volcanic unrest, landslides, and flood events), including seismic, GNSS geodetic, and other geophysical instrumentation with real-time or near-real-time telemetry to capture transient signals associated with these events for research hazard assessment and risk reduction.
3. Fully GNSS-capable antenna, receiver, power, processing, and telecommunications systems that acquire GNSS observations from constellations that are not yet launched, not yet operational, or otherwise not fully deployed, and deliver associated data streams in real time.

In the remainder of this section, we describe IRIS's plan to acquire portable instrumentation for full wavefield imaging and IRIS's role in the joint IRIS/UNAVCO effort to obtain state-of-the-art seismo-geodetic rapid response capabilities.

Scientific Need

Full Wavefield Imaging. Deployment of large arrays of sensors and relatively recent methodological advances such as ambient noise tomography (e.g., Shapiro et al., 2005; Duputel et al., 2009; Larose et al., 2015; Mordret et al., 2016), scattered wave imaging (e.g., Chaput et al., 2015), and full wavefield imaging (e.g., Nakata et al., 2015) now allow for much higher resolution imaging of Earth structure and seismic source properties. Because the fundamental physics of these wavefield techniques is spatially and frequency independent, these methods are applicable from the global and continental scale to scales of meters or kilometers, given appropriate types of sensors (to sample the requisite seismic frequencies) deployed in sufficient numbers to provide the necessary spatial coverage.

A series of IRIS and community meetings explored the range of scientific targets for full wavefield imaging, including earthquake physics and hazards, Earth structure, volcanic processes, environmental studies, and the cryosphere (**Table ISF1-1**). Numerous demonstrations of wavefield imaging of the continental crust and mantle have been obtained from data acquired with the EarthScope Transportable Array (e.g., Schmandt and Lin, 2014; Hopper and Fischer, 2015; Shen and Ritzwoller, 2016). Applying wavefield techniques such as ambient noise imaging to these data have resulted in unprecedented improvements in resolving crust and mantle structure within the North American continent (e.g., **Figure SD-2**). Dense deployments of nodal instruments across the top of Mount St. Helens (Hansen and Schmandt, 2015; Kiser et al., 2016; **Figure ISF1-1**) and the San Jacinto Fault (Ben Zion et al., 2015) demonstrate the power of using dense sensor deployments to illuminate the interior of volcanoes and major active fault systems on scales of just tens to hundreds of meters. IRIS recently hosted a community Wavefield Demonstration Experiment to better understand advances in imaging realized from wavefield experiments, and to provide the community with experience in planning and deploying wavefield arrays. This demonstration experiment incorporated several array designs and multiple instrument types (nodal high frequency, broadband, and infrasound) in an active seismic area in Oklahoma (see **sidebar** on page 46).

Rapid Response To Geohazards. Many important Earth processes are ephemeral and presently unpredictable. Advancing scientific understanding of these events requires mobilizing, deploying, and operating instruments on short notice. Aftershock studies and volcanic eruptions are examples of phenomena that require rapid response. Most significant earthquakes occur in locations that have, at best, regional seismographic coverage with station spacing of many tens to hundreds of kilometers. Many earthquakes occur in areas with no regional seismographic coverage. Rapid deployment of portable seismographs is essential if we are to capture the evolution of the aftershock sequence to better understand

TABLE ISF1-1. Science targets enabled by wavefield imaging/dense sensor deployment approaches.

Earthquake Physics	• Distribution and timing of seismicity clusters • Fault slip evolution during earthquakes • Deep fault structure • Inter-earthquake evolution of faults with time • Interconnections among slip, tremor, and earthquakes
Structure/ Imaging	• Earth structure without spatial aliasing and associated spurious imaging artifacts • Crustal structure and properties (e.g., velocity, density, anisotropy, attenuation) • Lithosphere-asthenosphere transition structure • Mantle and core structure (e.g., scatterers, phase and compositional transition structure), including global modeling
Volcanoes	• Temporal changes associated with intrusion and eruption • Seismic interferometry and 4-D monitoring of volcanic systems
Energy and the Environment	• Improved facies characterization • Imaging geology beneath high-velocity surface layers • Improved porosity/permeability estimates • Mapping thin layers with P and S attributes • Seismic interferometry and 4-D monitoring of reservoir systems
Polar, Fluvial, and Cryosphere	• Bed and subglacial Earth structure • Ice structure and glacial seismicity • Climate change influences on glacial systems; impact of sea level rise on calving glacier systems • Seismogenic processes of rivers, englacial and subglacial flow, and coupling with the solid Earth and ocean
Hazards	• Operational aftershock forecasting • 4-D mapping of post-earthquake seismicity and stress/strain fields • Detection, mapping, and forecasting of eruptive activity • Pre-, syn-, and post-earthquake analysis of the behavior of the built environment

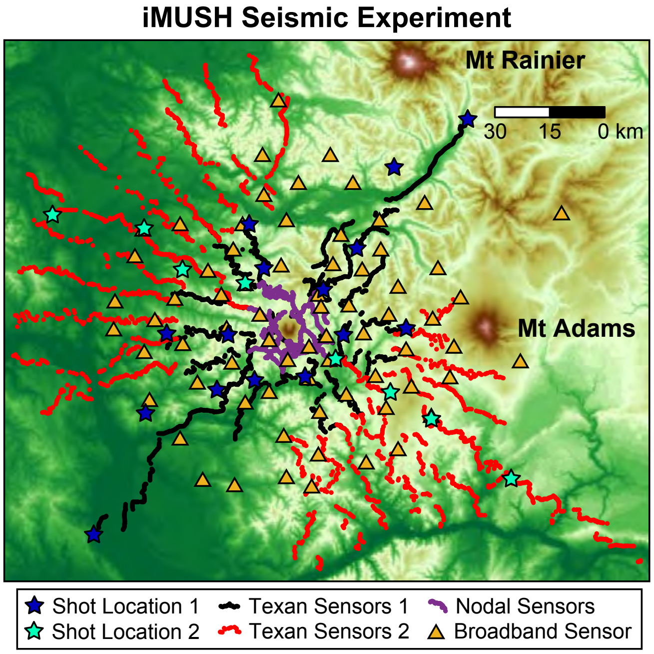


FIGURE ISF1-1. The deployment of nodal instruments across the top of Mount St. Helens for the iMUSH experiment is an excellent demonstration of using dense sensor spacing in a challenging environment. This experiment used nearly 6000 seismic sensors, including 70 broadband seismographs, 4981 geophones with "Texan" recorders deployed in two phases, and 920 nodal sensors.

the rupture process and coseismic and postseismic deformation, earthquake triggering, transient changes in material properties, and fault zone healing, and to image fault networks. With deployment of sufficient numbers of local sensors, the seismic illumination provided by aftershocks can be used in association with newly developed imaging techniques to constrain the spatiotemporal evolution of the earthquake rupture volume (Davenport et al., 2015) and the relationship between seismic and aseismic slow slip and low frequency events.

The monitoring and study of volcanic hazards is also greatly facilitated by access to equipment that can be rapidly mobilized. Unlike most earthquakes, precursory seismicity, tremor, and other phenomena often provide indications of an impending eruption. Modern portable instrumentation, deployed at newly realizable scales, can now enable 3-D and 4-D imaging and monitoring of volcano magma transport systems. Studies such as those on Mt. Erebus (Zandomeneghi et al., 2013) and Piton de la Fournaise (Duputel et al., 2009; Peltier et al., 2009) demonstrated the enormous value of comprehensive and dense geophysical instrumentation around and on a volcano. The wide distribution and large number of potentially active volcanoes in the United States and worldwide means that most will remain uninstrumented for the foreseeable future. Rapid response capabilities, informed by remote sensing or other early indications of activity, are essential for scientific progress.

The Frontier Challenge

Full Wavefield Imaging. The use of wavefield imaging techniques requires deploying seismic instruments in much larger numbers (hundreds to thousands) than has previously been feasible. Making such deployments practical requires instruments with significant reductions in size, weight, power, and cost. Wavefield imaging strategies use sensors that are optimally matched to signal frequencies and wavelengths, allowing researchers to deploy a mix of sensors that cover different parts of the frequency-wavenumber spectrum. For shorter wavelength signals, observations can be made using lighter, compact, less expensive, higher frequency sensors deployed at the greatest spatial density, while longer wavelength signals can be simultaneously recorded with a sparser array of intermediate-period sensors, and the longest wavelengths by a still smaller number of widely spaced full-broadband instruments.

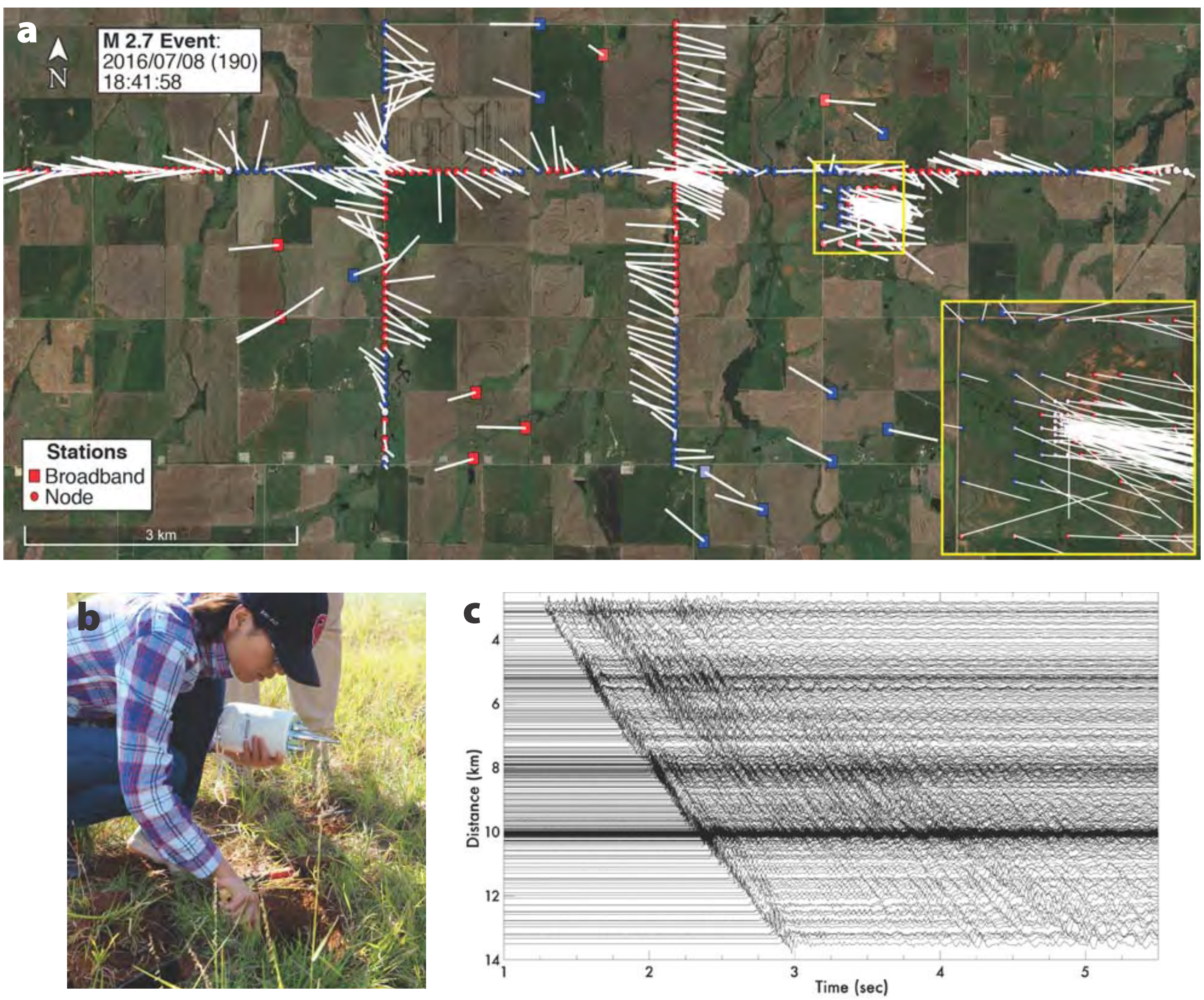
The frontier challenge is that the necessary systems for these mixed frequency response deployments do not exist within the present PASSCAL instrument pool. We must identify, test, and evaluate the existing or emerging technology that can be adapted to these scientific needs, and work with vendors to develop and build new systems where necessary. A further challenge is to integrate mixed instrumentation populations more effectively in field operations and in data handling and archiving procedures. This frontier activity will provide the NGEO with a core pool of instruments that can support transformative research from the critical zone to the deep Earth using wavefield imaging techniques.

Rapid Response To Geohazards. New and emerging seismograph technologies offer significant improvements for addressing challenging environments commonly associated with geohazards. In particular, recent technological developments have reduced the size, weight, and power of available systems, making them far easier to transport to the field, with attendant improvement in response time (days as opposed to weeks). Real-time telemetry, an emerging new capability for portable instruments, will be a game changer by allowing investigators to immediately assess ongoing activity, adapt their response while in the field, and provide more timely information to inform hazard monitoring and recovery efforts. However, implementing real-time telemetry will be challenging, given that these systems must work in a variety of different environments, be easily set up by non-experts, and be robust and operate within limited power budgets. Finally, there is the challenge of seismo-geodetic integration at the instrumentation level. IRIS will work closely with UNAVCO to define scientific needs and real-world operational use cases, while simultaneously solving the technical challenges of power, packaging, communications, and operability.

Wavefields Community Demonstration Experiment

In response to the high level of community interest in wavefield observing techniques, IRIS conducted a Community Wavefield Demonstration Experiment in Oklahoma in June 2016. The experiment provided the community with experience in new acquisition techniques for obtaining full wavefield observations using a range of instrumentation at multiple spatial and temporal scales. Diverse experiment targets were put forward by the community as part of an open competition, including urban environments, river deltas, microseismicity in active fault zones, geothermal production areas, and induced seismicity. The final experiment design combined multiple deployment geometries for targets in Oklahoma. Roughly 50 participants from 21 different institutions (including 30 graduate students) participated in the experiment.

Instruments were deployed in multiple array configurations (a), including a gradiometer consisting of instruments set out in concentric squares, a "golay" array of broadband instruments (squares) set out in six aligned equilateral triangles, and linear arrays (circles), in a multi-cross arrangement with strategically densified subdeployments. The experiment used both state-of-the-art 5 Hz, three-component nodal sensors (b), of the type that are rapidly gaining market share in the energy exploration business, combined with broadband and infrasound sensors. Data return was excellent, including 100% return from the nearly 400 deployed nodes (pending data recovery from two damaged units), and excellent waveforms were recorded by both the nodes (c) and broadband instruments.



(a) The complex nature of seismic wavefields is illustrated by this snapshot of a P-wave from an M2.7 earthquake (approximately 8 km NW) crossing the array. The three-dimensional ground motion is illustrated by the symbols—vertical and horizontal motion are represented by colors red (up) and blue (down), and white lines, respectively. The inset map provides a closer look at the gradiometer array contained within the network footprint. The basemap uses a recent satellite image of the study area. (b) Student deploying an ultra-portable nodal sensor (she is holding the sensor in her left hand). (c) Vertical component record section for the same event, including all available nodes and broadband stations. A highly coherent P-wave arrival spans the entire array. Numerous coherent signals in the P-wave coda indicate that the array is able to image complex structure with very high resolution.

Proposed Activities

Wavefield Imaging Capability. This frontier activity will provide the NGEO with a state-of-the-art wavefield imaging capability that will address needs across the widest user-specified frequency-wavenumber spectrum possible, while minimizing compromises in performance and packaging. We will work closely with the research community to ensure the needs and specifications are identified and addressed across diverse relevant applications. Based on extensive discussions to date, we expect to focus on acquiring two specific capabilities: nodal-style high-frequency instruments and intermediate-period posthole-capable sensors. These instrument types also encompass the area of greatest current need relative to existing facility capabilities.

We will pursue two parallel paths for this acquisition effort, as the state-of-the-art and economics of high-frequency nodal-style systems are somewhat different from that for intermediate-period systems. In both cases, we will begin by defining and communicating user needs and requirements with technologists and vendors via meetings, through requests for information, and by inviting vendors to participate in open community workshops and other meetings. Risks will be managed through test and evaluation of candidate technologies, working closely with vendors, and demanding testing of newly developed technology. We expect to procure a small quantity of instruments initially (i.e., low-rate initial production) to ensure vendor(s) can successfully manufacture the instrument and meet community-defined performance requirements. We will also support community members to use trial systems in pilot experiments to ensure they meet these requirements in actual deployments prior to any larger procurements.

In the case of nodal instruments, we propose to use a combined own/lease strategy. We will maintain a core nodal capability in the facility instrument pool to support smaller and mid-sized experiments where leasing may not be cost effective, and experiments requiring short mobilization times, or that are located overseas or in high-risk settings where leasing may not be feasible or appropriate. To create a capacity to support very large wavefield imaging experiments (e.g., experiments involving up to many thousands of instruments) we will augment this core capability with leased instruments. It is common for nodal-style instruments used by the energy industry to be available via lease, and we will investigate brokering longer-term lease agreements to reduce prices from service providers and ensure some level of availability, regardless of fluctuations in industry demand. Intermediate-period seismographs are not heavily used in the energy or other industries at this time, and we expect few, if any, associated leasing opportunities. Thus, we will very likely have to rely on the acquisition of facility pool intermediate-period instruments that are uniquely suited to research seismology needs.

We will develop best practices and training materials to accompany the new technologies and capabilities that are integrated into the NGEO portable instrumentation facility. We will demonstrate these new technologies to the community, provide training on deployment methods, and facilitate the sharing of strategies for experiment design. While final numbers will depend on details to be determined through the process described above, we believe that we will be able to add on the order of 1000 three-channel, nodal sensors and ~380–400 intermediate period, posthole-capable seismic sensors to the PASSCAL instrument pool (**Figure PS-5**). This should meet current demands from PI experiments and reflects a reasonable investment in hardware for the NGEO. As noted above, we will also facilitate leasing arrangements to meet demand for experiments using larger numbers of nodal instruments.

Rapid Response to Geohazard Events. A rapid response capability is part of the existing seismic and geodetic facilities, but is underdeveloped relative to its potential. With the availability of new technology, we see an opportunity to address community aspirations while growing NGEO ties to the geohazards community. This frontier activity will include substantial collaboration with UNAVCO to explore integrated seismo-geodetic systems for rapid response studies. We envision a rapid response equipment pool that is kept readily available, is easy to ship and deploy, and is fully capable of collecting critical research-grade data (i.e., high-signal-to-noise, on-scale seismograms), as well as a staff that can support these systems and assist with immediate training of PIs and deployment of the systems.

This effort will begin with a focused workshop to define the community's use cases, unconstrained by prior practice or by specific past instrumentation. Seismo-geodetic rapid response system design and integration will be dictated by both user requirements and available technology (some vendors are already developing integrated seismic-geodetic instruments). We will also explore modular integration of systems at the subsystem level, such as via common power or telemetry. Such systems will allow seismic and geodetic sensors to be operated at either coincident or separate locations. While final numbers depend on details to be determined in the above process, the budget would permit us to acquire on the order of 200 nodal-type, three-channel sensors and ~50 intermediate period, posthole-capable seismic sensors for the PASSCAL instrument pool that would be dedicated to rapid response studies.

Telemetry-enabled units will provide a wholly new capability for community rapid response experiments. There are multiple communications topologies (e.g., ad hoc mesh networking, spoke and hub) and technologies (e.g., point-to-point, satellite) that will be evaluated. While we have substantial experience with these technologies, their use during rapid response scenarios is particularly challenging. Thus, we will also explore how existing operational models should be altered to realize the numerous benefits that telemetry will provide. We will also address other issues, including accommodating international laws for importation, licensing, and use of the radio spectrum; developing procedures (for non-experts) for establishing and monitoring network topologies; and connectivity.

Two additional capabilities will be developed for this rapid response equipment pool. For aftershock studies in particular, we will incorporate accelerometers into the rapid response equipment pool for strong motion recording up to 1–2 g (to complement seismometers, which begin to clip at acceleration levels of a few percent of g). Some responses will require placing instruments in high-risk locations that might be subject to damage from lava or ejecta, inundation, or very strong shaking. We will need to create hardened systems coupled with deployment strategies (e.g., use of drones) that minimize risk to field personnel, while ensuring quality operations and maximum data return.

At the operational level, we will provide a common NGEO mechanism for requesting and reserving seismic and geodetic equipment, obtaining import/export assistance, and providing staff support. International issues, in particular, can be technically and legally complex, and require professional support to ensure adequate and timely readiness and response. We will also provide, if needed, expertise and coordination with federal and state agencies on domestic and international responses.

We note that the capability proposed here is quite different from the NSF's Rapid Response Research (RAPID) Facility recently funded at the University of Washington as part of the Natural Hazards Engineering Research Infrastructure facility. The RAPID capability is focused on rapid response and data collection related to the effect of earthquakes and windstorms on civil infrastructure. The capabilities we propose for the NGEO are broader in the spectrum of Earth motion observed, and much more diverse in application, including earthquakes, volcanic eruptions, landslides, glacier movement, explosions, and ambient noise.

Seismo-Geodetic Seafloor Instrumentation – WBS 1.1.7

Water covers two-thirds of the Earth. The ability to make long-term seismic, geodetic, and other geophysical observations on the seafloor is essential to fill substantial gaps in imaging Earth's deep interior. We propose a joint IRIS/UNAVCO effort to develop, construct, and test prototype integrated and stand-alone seismo-geodetic seafloor observatories. This frontier activity will address two high-priority applications: cross-coastal geophysical studies that can seamlessly extend land-based studies into the offshore environment, and long-term broadband seismic and geodetic observations in remote ocean locations in order to obtain complete global network coverage. Our goal is to propel seafloor geophysical instrument, data communications, and data systems technology forward within the first five years of the NGEO, with the intention of seeking longer-term funding outside of the NGEO for the large-scale procurement and deployment of these newly designed seafloor geophysical systems.

Scientific Need

Many of Earth's most important processes can only be fully understood if we collect observations using sensors placed on the seafloor. Virtually all of the Earth science grand challenges and community vision documents produced by the Earth science community in the last 10 years (e.g., *Seismological Grand Challenges in Understanding Earth's Dynamic Systems* [Lay, 2009], *New Research Opportunities for Earth Sciences* [NRC, 2012], *A Foundation for Innovation: Grand Challenges in Geodesy* [Davis et al., 2012], *Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences* [Aster and Simons, eds., 2015]) call out the critical need for improved offshore seismological and geodetic observations—the need to cross the "line" that separates onshore and offshore scientific research. The "Futures" Facility Workshop Report recommends that "*future facilities should have the capacity and resources to install, maintain, and exploit dense seafloor geophysical observatories*" (Aster and Simons, eds., 2015, p. 40). The NGEO facility provides the ideal forum for addressing, coordinating, and ultimately implementing this capability.

Seafloor observations are crucial for making transformational advances on fundamental solid Earth science questions. In particular, the relative scarcity of these observations in cross-coastal settings has limited progress in understanding subduction zone processes (e.g., Rosen, 2016), especially megathrust slip on the interface of subducting plates. The 2011 Tōhoku earthquake showed large fault slip in the updip section of the plate interface (Simons et al., 2011; Kodaira et al., 2012), when previously this section of the plate interface was thought to be continuously creeping (Moore and Saffer, 2001). Despite their distance from the coast, earthquakes associated with these events often cause devastating tsunamis (Lay et al., 2010). Fault behavior in subduction zones cannot be constrained by geodetic and seismic observations made only on land (Hyndman, 2013; **Figure ISF2-1**). Offshore seismic capabilities, as they exist today, are insufficient for systematic, long-term subduction zone studies, such as those that might be part of a future Subduction Zone Observatory; currently there is no U.S. offshore geodetic facility of any kind.

The ocean also remains a vastly undersampled region from a global geophysical perspective. The establishment of approximately 20 high-quality permanent seismic stations in the ocean has long been envisioned to complement the data from the existing high-quality very broadband GSN network on land. Remote ocean GSN-quality stations would provide real-time recordings of earthquakes not well recorded or located by existing land-based seismic networks and would increase the resolution of seismic models of Earth structure beneath the ocean, including phenomena such as mantle plumes (Wolfe et al., 2009) and the South Pacific Superswell (McNutt and Judge, 1990; Tanaka et al., 2009). Only seafloor observations can provide the detailed resolution of ocean plate structure and seismic anisotropy required to understand the oceanic lithosphere-asthenosphere system (Takeo et al., 2013; Lin et al., 2016). Seafloor seismographic data are also critical for both national and international agencies in monitoring and characterizing earthquakes, tsunamis, and nuclear explosions.

The Frontier Challenge

Obtaining long-term, telemetered, high-quality geophysical observations in the remote ocean is feasible now due to recent technological advances in timing, power, shielding, telemetry, and autonomous vehicles (**Figure ISF2-2**). These technologies will permit the scientific community to address the numerous compromises that often must be made with short-term, campaign-style seafloor seismic observations such as limited-duration deployments due to battery capacity, lack of real-time communications, and high noise due to suboptimal sensor emplacement techniques. The nascent field of seafloor geodesy presents even more challenges, both in terms of creating a system that yields the required precision, accuracy, and spatial distribution over time, as well as an operational model with realistic costs.

Key challenges for deploying seafloor seismic capabilities include system packaging, shielding from bottom currents, and sensor emplacement relative to short-period, long-period, and strong motion performance. Power consumption is always a concern, as it directly impacts observing duration. However, the commercial and defense sectors are driving advances in battery technology that can be applied to ocean bottom instruments. Timing technology is also critical for long deployments, and technical breakthroughs are occurring in this area as well.

Multiple techniques are available for making seafloor geodetic measurements (Bürgmann and Chadwell, 2014). Choosing the right approach must balance scientific goals with capability and operational feasibility. Technologies such as point-to-point acoustic ranging measurements on the seafloor, GPS-acoustic methods with a GPS-enabled surface vehicle using acoustic ranging to seafloor monuments, pressure measurements for vertical deformation, and tilt and borehole strain measurements to detect seafloor deformation are all relevant technologies, each with their own advantages and disadvantages.

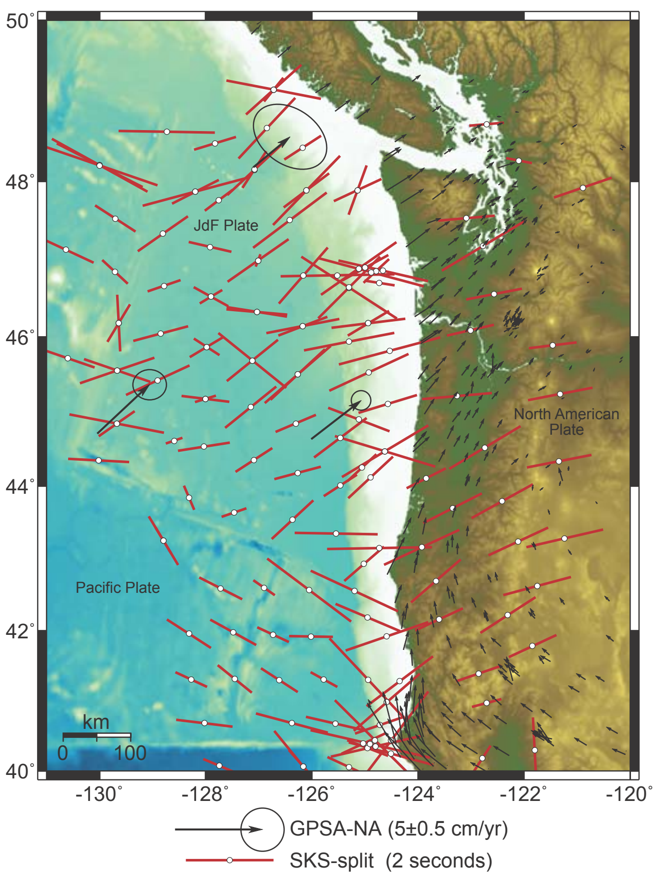


FIGURE ISF2-1. Inferences of mantle flow from SKS splitting observations (Martin-Short et al., 2015) combined with plate motion observed from offshore acoustic GPS (GPS-A) measurements (adapted from Chadwell et al., 2015) and on-land PBO and Pacific Northwest Geodetic Array GPS observations (Schmalzle et al., 2014) from the Cascadia region. Using land-based measurements alone, the complexity of mantle flow and deformation of the subducting Juan de Fuca Plate seaward of the Cascadia subduction zone cannot be determined.

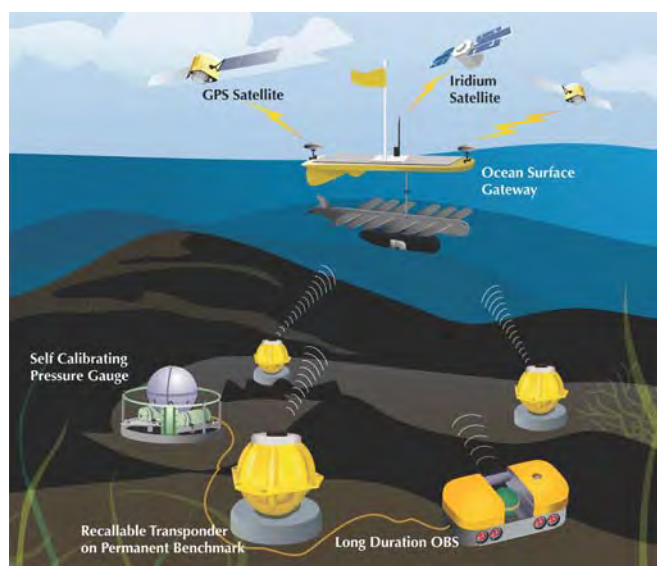


Figure ISF2-2. System concept for a long-term, cross-coastal, open-ocean seismo-geodetic seafloor station. A station site uses an ocean bottom seismometer, an absolute pressure gauge, and geodetic monuments. The seismometer and pressure gauge share a communications interface to the surface gateway, which transmits the data via satellite. The transponders on the geodetic monuments are either doing point-to-point acoustic ranging or GSP-acoustic ranging to the GPS-enabled surface gateway. *From J. Orcutt, pers. comm. (2016)*

Other challenges include determining how closely the seismic and geodetic measurements should be integrated. To gain a full understanding of complex ocean processes requires collecting both seismic and geodetic observations, but the appropriate level of sensor and data flow integration in a seafloor observatory must be determined based on science objectives, technical trade-offs, operational models, and costs. Data retrieval from seafloor instruments is another challenge. Telemetry technology required for ocean floor observatories has been demonstrated in prototype form (Frye et al., 2005; Berger et al., 2016) with moorings and autonomous surface vehicles (e.g., Wave Glider). Other data retrieval techniques include offloading data via an optical modem to a loitering autonomous underwater vehicle or to a modem lowered from a ship. Another innovation is to periodically release data "bubbles," small buoyant capsules with data in flash memory that can be retrieved by a ship or telemetered to shore via an Iridium satellite upon reaching the sea surface.

At this time, there is no single sensor or data system that has received broad community endorsement. We propose a comprehensive and integrated development approach that starts with community input on scientific and operational needs. Based on this input, we will evaluate the multiple potential technical solutions and determine the strengths and weaknesses of each solution with respect to performance, operations, and cost.

Proposed Activities

Creating an NGEO capability for long-term seafloor observations, while challenging, is within reach and holds the promise of enormous scientific payoff. IRIS/UNAVCO will use an open and inclusive process to engage the scientific community in fully defining scientific needs, engineering requirements, and potential technological solutions. In order to obtain this vital information, we will hold a workshop that brings together scientists and technologists, and will form a similarly diverse steering group to guide the development effort and ensure that community input guides the path forward so that the development process yields a system that meets community needs.

Our technology development effort will proceed, with requirements definition and design reviews, technology testing, and validation, leading up to at-sea trials of initial prototypes. We will consider including additional sensors, such as electromagnetic for MT studies, during the design stage. For efficiency, we will use a single development approach, but with off-ramps to specific applications (cross-coastal; GSN). The design and development work for the seismic components proposed here will be done through subawards to the OBSIP instrument centers to utilize their knowledge and technical expertise in ocean bottom seismology.

To ensure quality and agility in our processes, we will tailor systems engineering best practices to our needs, and these will guide our activities in a structured way, from establishing user requirements through to rapid prototyping. We will take full advantage of the substantial expertise that exists within the marine community by utilizing open, competitive subawards to design, develop, test, and integrate the required technologies. Risks will be managed through utilization of systems engineering best practices with tests to validate technology throughout the process. We will make judicious use of subawards for developing competing solutions, with subsequent down-selection, where warranted and/or necessary. The entire process will pay particular attention to developing and defining a concept of operations, as this ensures that all stakeholders have a common vision of how the final system(s) will operate. This also ensures the resultant systems fit within realistic operating budgets for NSF-supported ocean-going experiments. To this end, we will hold a Mission Concept Review at the end of the second year to ensure that the concept of operations, design, expected operational costs, and expected performance are all in alignment.

We recognize that a seismo-geodetic seafloor observing capability is of fundamental interest to both the Earth and Ocean Science Divisions of the NSF, and the path forward from development, through to testing, and eventual operations and maintenance must fit into the science and facility plans of both divisions. We envision this seafloor frontier project as a decadal effort with two phases. In the first phase, during the first five years of the NGEO, we will execute the steps described in this proposal to design and build prototype(s) for making long-term seafloor seismo-geodetic observations. The second phase of this project, during the next five years of the NGEO, will entail comprehensive field trials and the procurement and deployment of systems to support PI-driven or community experiments. We envision funding for the second phase of this project will come from sources outside of the NGEO, and we have not budgeted for those costs in this proposal. While the proposed development effort is underway, we expect community planning for both experiments such as subduction observatories (see Rosen, 2016, and the recent NSF-sponsored Subduction Zone Observatory workshop) and seafloor GSN stations will have advanced to the point that both the scientific merit and technological capabilities of seafloor observatories can be evaluated by the NSF and an appropriate paths forward and funding options for procurement and operational deployment of these systems can be identified.

Geophysical Data Services and Products – WBS 1.2

INTRODUCTION

IRIS, working in close collaboration with UNAVCO, will develop an NGEO Data Management System that will provide seamless access to all data collected by the NGEO facilities. In order to provide this new capability, we will leverage work done by IRIS and UNAVCO as part of the European-funded Cooperation Between Europe and United States project and the NSF-funded EarthCube GeoWS project. From those projects, we learned how to use web services to build federated networks of international data centers and how to deploy web services across geoscience domains. In the NGEO, we will take the next step and use techniques developed for GeoWS to provide seamless access to data managed by both IRIS and UNAVCO.

A user will be able to enter the NGEO Data Management System through a single NGEO Data Access Point (NDAP) to discover and access all NGEO data (**Figure DS-1**). The NDAP will support the specification of a single space-time parameter consistent with an individual's research needs. Because users entering the system through the NDAP may not always be able to utilize domain-specific formats, data will also be available through a variety of formats, including a common GeoCSV one. Domain experts will still be able to access UNAVCO and IRIS directly through supported web services and other tools they currently use.

The NGEO Data Management System will initially be a distributed system with two separate, but linked, data centers maintained by IRIS and UNAVCO with an integrated Auxiliary Data Center (ADC) that serves as a full service, but unmanned, backup facility for both centers (**Figure DS-1**).

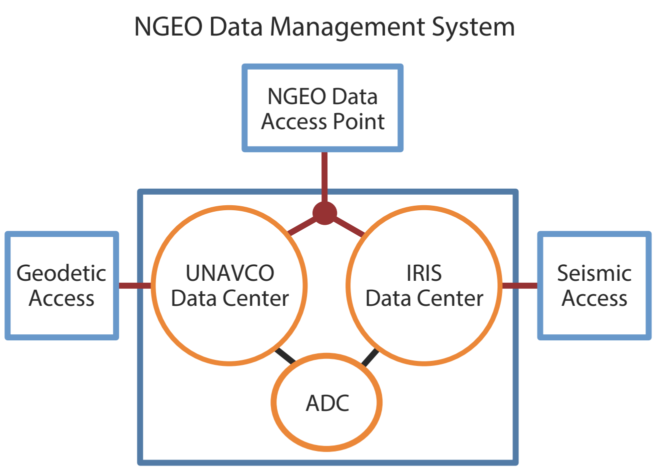


FIGURE DS-1. IRIS and UNAVCO will develop an NGEO Data Access Point through which all NGEO data will be available for integrated queries to our distributed facilities. Both the IRIS and UNAVCO data centers will maintain computational infrastructure at their facilities, but will share a single Auxiliary Data Center (ADC) hardware and software infrastructure for redundant capabilities.

The expertise needed to manage the multitude of data types in the NGEO currently resides at the existing UNAVCO and IRIS data centers in Boulder, Colorado, and Seattle, Washington, respectively, and we will keep domain knowledge close to where the data physically reside to maximize continuity of operations.

While our initial plan is to operate our current hardware and software systems at the existing IRIS and UNAVCO data centers, together we will move the ADC into a cloud environment during the first few years of the NGEO. The best cloud infrastructure to use for this purpose is currently being evaluated through the NSF-funded EarthCube GeoSciCloud project. Based on our experience with GeoSciCloud, we will consider eliminating most hardware at IRIS and UNAVCO and moving all of our data archive and computational needs into the cloud during the NGEO award period if that provides the most cost-efficient operational model for the NGEO.

In addition to building the NGEO Data Management System and Data Access Point, IRIS and UNAVCO will jointly develop a new frontier data service: Connecting Big Data to HPC and the "Cloud." This frontier data service will be a cooperative effort with the NSF-funded Computational Infrastructure for Geodynamics (CIG) consortium. Building on the GeoSciCloud project, we will address the "Big Data" bottleneck by making the NGEO data available in close proximity to significant high-performance computing (HPC) and cloud computational resources, such as the Extreme Science and Engineering Discovery Environment (XSEDE). XSEDE is an NSF-funded virtual system that supports 16 supercomputers and high-end visualization and data analysis systems across the United States that scientists can use to interactively share computing resources, data, and expertise (Stewart et al., 2016). By locating the NGEO data close to significant computational resources, we will transform the way our community conducts compute-intensive research in the same way that IRIS's development of automated computer-to-computer data access has revolutionized the way our community obtains data.

FOUNDATIONAL DATA SERVICES

IRIS Data Services – WBS 1.2.1

IRIS is recognized as a world leader in the management of time-series data in the geosciences. IRIS adheres to two key principles in its approach to data services: (1) continuous data should be recorded and retained as long as resources are available, and (2) these data should be freely and openly available to any interested user without restrictions. Through its promotion of free and open access to data, IRIS has changed the culture of scientific data management in the geosciences and broadened the field of seismology to include researchers at organizations of all sizes worldwide. The improved efficiencies in data discovery, management, and retrieval enabled by the IRIS DMC have increased the productivity of researchers and improved the science they produce. In 2012, an external panel consisting of international and national experts in seismology and data center operators reviewed IRIS Data Services (DS). Their report stated that they were: "*impressed by the level of service to the seismological community provided by IRIS Data Services. Data is received and made available for use in very efficient ways and this has resulted in heavy demand for data delivery*."

IRIS maintains the largest facility in the world for the archiving, curation, and distribution of seismological data from permanent and temporary seismological observatories and experiments. The IRIS DMC supports flexible management of time-series data, and includes data from approximately 30 kinds of sensor networks including magnetotelluric, electric and magnetic field, strain, gravity, creep, wind speed and direction, temperature, humidity, rainfall, solar radiation, barometric, infrasound, hydroacoustic, pressure, water current, water depth, and water level. If the metadata can be described in the SEED (Standard for Exchange of Earthquake Data) format, the IRIS DMC can manage the data.

IRIS has worked closely with the worldwide seismology community in the development of new formats, access mechanisms, quality control initiatives, and many other activities related to the management of geophysical data. IRIS is an active member of the FDSN and has played a lead role in setting international domain standards in the seismological community. These activities include the development and maintenance of the SEED format, including documentation and initiation of new standards for geophysical time series.

IRIS, working with other data centers, led the development of standardized web services in seismology and their deployment worldwide. This distributed system allows access to data centers around the world. Establishment of standard data access methods has enabled the development of a wide range of client-side software by the seismological community. With open-source software such as ObsPy and interface libraries allowing data to flow directly into commercial systems such as MATLAB, along with some key IRIS-developed clients, researchers have many ways in which to seamlessly access data from worldwide, federated data centers, greatly improving the efficiency of scientists in pursuing their research interests.

Description and Capabilities of the IRIS DMC

There are three core activities in the DMC: data ingestion, data curation, and data distribution. In addition, IRIS maintains state-of-the-art quality assurance systems, supports scientific software, and generates higher-level data products for the research community.

Data Ingestion. Data ingestion at the IRIS DMC includes both real-time and non-real-time data. **Figure DS-2** shows the growth of the archive from 1992 to the middle of 2016. The archive currently contains over 400 terabytes of time-series data and is growing at a rate of more than 70 terabytes per year.

Data Curation. Data curation is the continual management, updating, and maintenance of data to international standards. IRIS is a member of the World Data System (WDS) of the International Council for Science. As such, IRIS is certified and follows standards and best practices of the WDS. IRIS operates a fully redundant Auxiliary Data Center 1000 km from its primary center in Seattle to ensure that the archive is protected from any catastrophe. Data are routinely served from both centers to the end-user community. In the event one center fails, the other can meet much of the community's needs in a timely fashion. The uptime, a measure of how often a user could get data from at least one of the centers, is continually monitored, and for the past two years has been 99.94%. The DMC migrates data assets from one storage mechanism to newer storage systems roughly every four to five years. For the first two decades of the DMC, data were stored in robotic tape systems, but the reduction in cost of disk systems now enables IRIS to have all data assets online. IRIS maintains four complete copies of the data: a copy on disk and a copy on tape at both the DMC and the ADC. Over the DMC's 28 years of existence, we have never lost data for any reason.

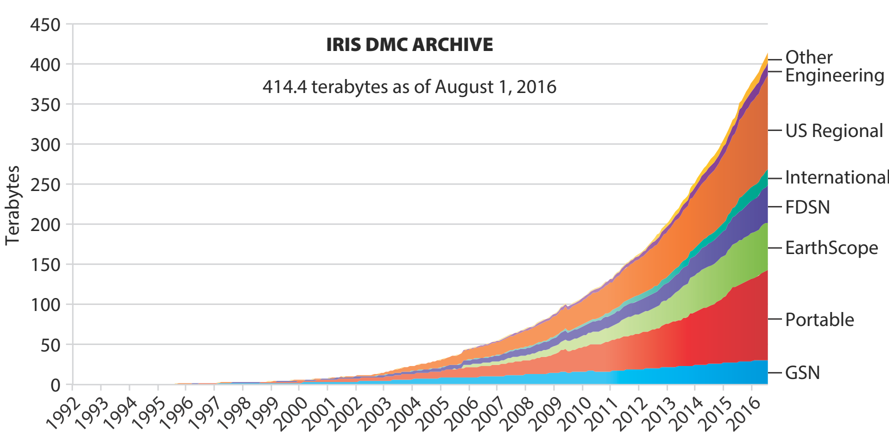


FIGURE DS-2. The IRIS DMC archive contains over 400 terabytes of data from multiple sources, including the GSN, portable deployments (PASSCAL, SEIS-UK, OBSIP, SISMOB), EarthScope, FDSN, non-FDSN, U.S. regional networks, and others. The archive is currently growing at more than 70 terabytes per year, and we anticipate this rate increasing with the inclusion of full wavefield deployment data.

Data Distribution. The DMC has pioneered methods through which users can request subsets of the data archive. These methods have evolved

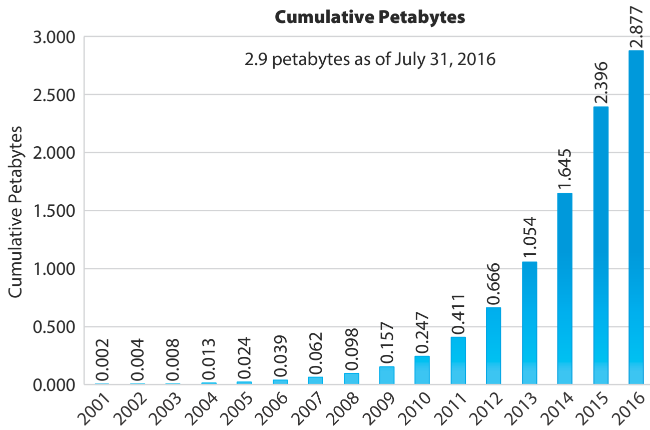


FIGURE DS-3. The ability of IRIS Data Services to meet the growing data requirements of the research and monitoring community is illustrated in this graph, which shows cumulative petabytes shipped since 2001. In 2016, the IRIS DMC provided access to roughly 0.9 petabytes of levels 0 (raw) and 1 (quality reviewed) waveform data. Roughly 12.5 times as much data left the DMC as new data entered the DMC in 2016.

from email-based mechanisms, to real-time data distribution, to the current very flexible web services that the broad seismological community has fully embraced. IRIS supports web services that allow seismological data to be reformatted for use by interdisciplinary scientists as well as the general public and K–12 future scientists. The use of web services for data requests has resulted in significant reduction in the amount of code that DMC staff maintains.

Seismological data are of two primary types: active source in industry standard formats such as those of the Society of Exploration Geophysics (SEG) SEG-Y and passive source in FDSN SEED format. A new development, initiated by the PIC, is to use HDF5 to manage both passive source and active source formats. HDF5 is a data model, library, and file format for managing data in a variety of data formats, and is designed for flexible and efficient input/output (I/O) and for high volume and complex data. IRIS DMC staff are currently extending web service interfaces into the HDF5 system that will enable seamless access to time-series data in these different formats.

The IRIS DMC distributes roughly 12 times more data to the research and monitoring communities than it receives annually (**Figure DS-3**). In 2016, IRIS distributed nearly 1 petabyte (1024 Tb) of data to users in over 170 countries. The DMC has data from more than 45 years, and each year researchers access data from each of those years. This level of data reuse is an indicator of the value of DMC resources and the need to maintain these data as long as resources allow.

State-of-the-Art Quality Assurance System. IRIS has taken the lead within the broader seismological community in the development of a comprehensive system to assess the quality of time-series data. The Modular Utility for STAtistical kNowledge Gathering (MUSTANG) is a system that calculates metrics related to data quality for most time series at the DMC. MUSTANG runs shortly after (one to two days typically) data are received at the DMC. These metrics serve as a diagnostic measure of the quality of data at IRIS. MUSTANG's logic detects when metrics need to be recalculated. This can happen when new versions of data are received, relevant metadata change, or when the metric algorithms themselves change.

Figure DS-4 shows a whisker plot of the number of gaps per day metric for the entire Nicaraguan National Seismic Network for the year 2015. Operators of the network can consult displays like this to easily identify problems with any stations in their network, quickly, reliably, and with minimal effort. IRIS seismic analysts routinely review MUSTANG output and generate succinct reports for seismic network operators. These reports allow the operators to identify problem stations, resulting in improved data quality. This value-added service provides impetus for networks to share their data with IRIS, making more data available to the seismological community. MUSTANG metrics are now being coordinated within the FDSN to standardize, where possible, the actual implementations of metrics on an international basis.

The Research Ready Data Sets project, now in development at the IRIS DMC, will enable requesters of IRIS data to specify constraints in any MUSTANG metric that will then be used as a filter to identify waveforms suitable for an end user's research. This service will improve scientists' efficiency because they will not have to cull the data themselves—the data they receive will be the data they need for their research.

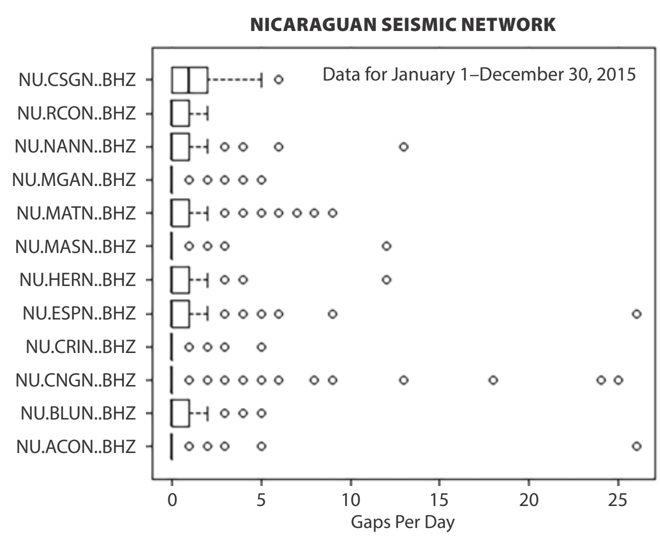


FIGURE DS-4. MUSTANG metrics can be displayed using standard whisker plots for any network that provides data to the IRIS DMC. The figure shows the statistical distribution of the number of gaps per day for the entire year of 2015 for the Nicaraguan National Seismic Network. The boxes near the left margin of the chart show the first quartile, median (bolder line), and third quartile in the distribution of this metric. The circles show outliers. The plot indicates that stations such as MGAN, CRIN, CNGN, and ACON have excellent data quality.

Support for Scientific Software. IRIS develops, supports, and maintains a wide variety of software, including client software primarily used for accessing data from the DMC. IRIS has developed a federated catalog service that currently allows client software seamless access to data managed at 16 FDSN data centers. This capability was enabled by the development of FDSN standard web services that was proposed, and to a large extent developed, by IRIS.

IRIS develops and supports tools that allow IRIS data to be used directly in existing analysis software systems. These systems include Seismic Analysis Code, licensed by IRIS from Lawrence Livermore National Lab (LLNL), MATLAB, and ObsPy (developed and maintained by the Ludwig Maximilian University of Munich). Additionally, the web services developed as part of GeoWS provide support for data output in GeoCSV, a format that is readily understandable and usable in any spreadsheet application. IRIS also supports the SeisCode software repository that consists of both IRIS and community contributed software for seismology.

Generation of Higher-Level Products. IRIS efforts to develop higher-level products are mature (Trabant et al., 2012). While Level 0 (raw data) and Level 1 (quality assured data) remain our primary products, we also develop Level 2 products derived from Level 0 and 1 data using straightforward, unambiguous methods. Level 2 products include such things as Ground Motion Visualizations (GMVs) and power spectral density plots. Level 3 products are the result of community research that has been peer reviewed, and they are managed by IRIS. They include Global Empirical Green's Tensors, Earth Model Collaboration (repository of researcher-produced tomographic models), and Syngine (synthetic seismograms generated on demand). In the NGEO, IRIS will focus on the management of new products developed by the community and the maintenance of in-house developed products. The products that IRIS makes available are diverse and widely used. In 2015, IRIS distributed more than 280,000 products. Currently, IRIS has no Level 4 data products. Level 4 products are those generated from the integration of data types. With NGEO funding, IRIS and UNAVCO will seamlessly integrate the data managed at both facilities and thus help the community to more easily generate integrated data products. IRIS has the infrastructure to host these products now and will do so as part of the NGEO.

External Data Coordination. IRIS Data Services conducts weeklong training courses for operators of seismic networks in all parts of the world. These courses emphasize the generation of correct metadata for the various time series, methods of transmitting data in real time to local centers and on to FDSN centers, state-of-the-art analysis systems, and seismic network management systems. An important aspect of these courses is conveying to participants that making data freely open and available in real time allows problems to be identified by a larger community, resulting in higher quality data. These courses have significantly increased the amount of data available for all seismologists from undersampled parts of the world. The monitoring agencies are also able to improve earthquake locations due to the increased global coverage.

Digital Object Identifiers. IRIS currently generates digital object identifiers (DOIs) (Evans et al., 2015) for all seismic networks that request a DOI. These DOIs can be viewed on pages IRIS maintains for the FDSN. IRIS also currently generates DOIs for all products managed at the DMC, which can be found on individual product pages on the Data Services website.

Research Supported by IRIS Data Services

IRIS is a primary information resource for the seismological and related research communities. Researchers can access either primary observational data from roughly 30 types of sensors distributed around the globe, or they can jump-start their research using IRIS-developed and/or IRIS-managed data products. Seismology, at its core, is an observational science, and IRIS-managed data provide much of the information needed to answer many geophysical questions. The global seismological research community benefits enormously from IRIS' strong connections to the FDSN and through bilateral connections between operators and the IRIS DMC (**Tables DS-1 and DS-2**) The broader geoscience community benefits from higher-level derived products IRIS provides that are more easily understood than raw time series.

The IRIS federated system operates across multiple data centers and makes globally distributed data available to anyone in a free and open manner. IRIS is also involved in brokered systems that can help build bridges between different types of geophysical data, working through EarthCube and members of its Council of Data Facilities.

Plans for the Facility Over the Next 10 Years

In addition to maintaining most of the current capabilities identified as foundational, IRIS and UNAVCO will pursue the development of several new capabilities for the NGEO.

Hosting Multidomain Data Sets Within the NGEO: Leveraging Current Capabilities and Existing Infrastructure. The highly successful IRIS and UNAVCO data centers serve the seismology and geodesy communities very well. With a strong foundation in place, IRIS and UNAVCO propose leveraging this existing infrastructure to expand the types of geophysical data managed in the NGEO. This NSF investment will enrich interdisciplinary Earth system science by making currently inaccessible data sets available to the broader community. Much of these data already exist, but in many cases they are not easy to access. UNAVCO and IRIS will develop next-

TABLE DS-1. Table listing states and countries that have signed a formal Data Provider Agreement (DPA) with IRIS DS. The DPA identifies the relationship between the data provider and IRIS DS. Numbers in parenthesis indicate the number of networks that have signed an agreement within one country.

Alaska	Colombia	Kyrgyzstan (2)	Taiwan
Argentina	Costa Rica (2)	Malaysia	Tajikistan
Arizona	Cuba	Spain	Texas
Aruba	Dominican Republic	Myanmar	Timor Leste
Thailand	Ecuador	New Guinea	Uzbekistan
Brazil	Honduras	New Zealand	Venezuela
Cayman Islands	Indonesia	Nicaragua	Zambia
Chile	Jamaica	Nigeria	
China	Kazakhstan	Panama	

TABLE DS-2. FDSN member countries that have provided data to the IRIS DMC. These 54 countries represent the majority of all FDSN member countries.

Albania	France	Malaysia	South Africa
Argentina	Georgia	Mexico	Solomon Islands
Austria	Germany	Netherlands	Spain
Australia	Ghana	New	Sweden
Brazil	Greece	Caledonia	Switzerland
Canada	Iceland	New Zealand	Taiwan
Chile	Indonesia	Nicaragua	Tajikistan
China (2)	Ireland	Nigeria	Thailand
Colombia	Israel	Norway	Tunisia
Costa Rica (2)	Italy (2)	Poland	Turkey
Czech Republic	Jamaica	Portugal	United Kingdom
Denmark	Japan	Puerto Rico	USA
Ecuador	Kazakhstan	Romania	Vanuatu
EU	Kyrgyzstan	Russia	

generation data discovery, analysis, and analytical tools to ingest, manage, and distribute data from additional geophysical data sources identified based on community input and agreed to by the NSF. The NGEO Data Management System will do this in one of two ways (**Figure DS-5**):

- By ingesting data, generating metadata, and managing data directly within the NGEO Data Management System
- By developing web service-based interfaces to the data holdings held at distributed geophysical data centers

IRIS and UNAVCO gained experience managing interdisciplinary data sets through the EarthCube GeoWS project. In some cases we brought data into the IRIS and UNAVCO data centers, and in other cases we developed interfaces with distributed data collections and centers. The GeoWS work was a proof-of-concept effort. We will make these capabilities operational and available through the NGEO Data Access Point (**Figure DS-1**). IRIS and UNAVCO are considering incorporating the following types of data into the NGEO Data Management System: superconducting gravimeter data (Global Geodynamics Project), field gravity and magnetic measurements and permanent observatory magnetic data, volcano monitoring data (e.g., Smithsonian and WOVODAT), heat flow data, and time series data from ocean observatory networks (the U.S. Ocean Observatories Initiative, NEPTUNE Canada, and Japan's Dense Oceanfloor Network System for Earthquakes and Tsunamis); and expanding the types of strong motion seismic data (including engineering data from structures) and adding links to selected collections at the NOAA National Centers for Environmental Information. The IRIS DMC will also ingest, curate, and distribute near-surface geophysical data from the proposed Near-Surface Geophysics Facility.

Shared Data Center Infrastructure in the Cloud. IRIS and UNAVCO received funding to support an EarthCube Building Block project named GeoSciCloud. We will deploy web services, including those from GeoWS and large subsets of data from our data centers, in XSEDE, an NSF-funded HPC environment. GeoSciCloud will also deploy services and data assets in commercial cloud environments such as those provided by Amazon, Google, or Microsoft. GeoSciCloud will help IRIS and UNAVCO understand the costs, maintainability, serviceability, and performance of working in these different computing environments. We will compare the costs of running our data centers in the cloud with the costs of running on our own infrastructure. The GeoSciCloud project will inform our organizations as to the "best" infrastructure to support the NGEO Data Management System in the future in the most cost-effective manner.

The current IRIS architecture includes the IRIS DMC in Seattle and a fully functional ADC 1000 km away. In NGEO Year 1, IRIS and UNAVCO will begin moving their data center operations into the cloud environment identified by the GeoSciCloud project. In NGEO Year 4, we will begin expanding the capabilities of the cloud-based center and begin improving support for both HPC and elastic cloud capabilities that will enable improved services to the NGEO user community. The goal is to have all NGEO data managed within a single cyberinfrastructure that has significant storage

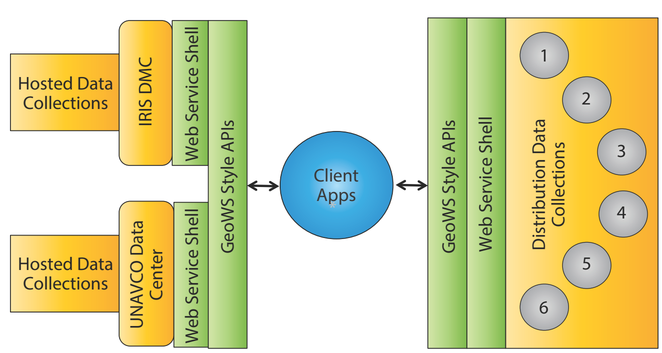


FIGURE DS-5. The NGEO Data Management System will expand the types of data it provides access to. Some data will be managed directly by ingestion into the NGEO Data Management System. When viable, other data will be left in place at their host institutions, but GeoWS style interfaces will be implemented to allow data discovery and access in a distributed manner.

and computational capabilities. We will leverage other parts of the NSF, such as the Directorate for Computer & Information Science & Engineering, specifically that directorate's Data Infrastructure Building Blocks program, to find the resources our data centers and our community of users will need. We anticipate the majority of the funding for this effort will come from non-NGEO sources.

Other Foundational Activities Planned for the NGEO

- Expanding the Seismic Data Center Federation to all parts of the world, including Asia and Africa
- Providing time-series data in current formats and expanding the types of data managed in SEED format
- Working with our FDSN partners to evolve and improve the SEED format
- Providing seamless access to passive and active source seismic data sets in multiple formats, including HDF5, a more interoperable format found in other domains
- Providing support for formats that are better suited for use in traditional HPC environments, including the Adaptable Seismic Data Format
- Enhancing support for user-friendly domain agnostic formats such as GeoCSV
- Improving the availability of online tutorials so that users have self-help resources at their fingertips
- Establishing a capability to support workflows in the cloud in close proximity to the data resources

Management and Organization

IRIS Data Services is a distributed system with the primary node (DMC) located in Seattle, Washington, where most of the IRIS DS staff work. Other nodes include Data Collection Centers for the GSN at the ASL and the UCSD, and in Almaty, Kazakhstan. The University of Washington Earth and Space Sciences Institute acts as the host of the IRIS DMC. The final DS node is located at DOE's Lawrence Livermore National Lab, which houses the IRIS ADC.

Most of the non-DMC nodes focus their attention on the creation and validation of the metadata that describe their stations and performing quality control on their network data. The DMC focuses on the ingestion, curation, quality assurance and data distribution activities. DMC staff remotely manage the infrastructure at the unmanned ADC.

Figure DS-6 shows how IRIS Data Services is internally structured. There are four operational sections: (1) DMC Operations, (2) Cyberinfrastructure, (3) Quality Assurance, and (4) External Data Coordination. Additionally, IRIS is very well connected with a number of domestic and international organizations that strengthen our data management capabilities, including the FDSN, WDS, Cooperation Between Europe and the United States, Earth Science Information Partners, and EarthCube, including its Council of Data Facilities.

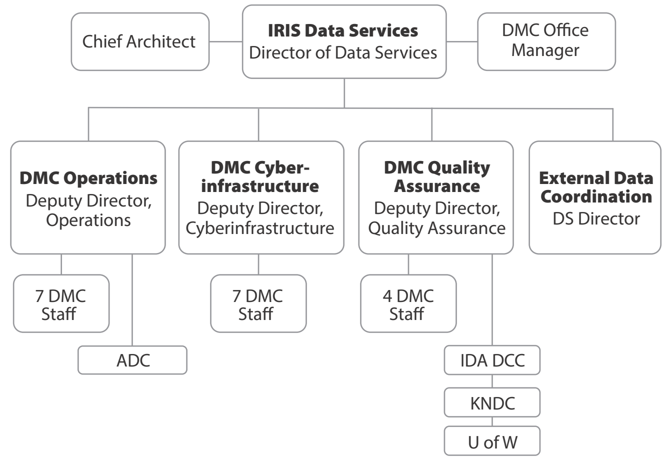


FIGURE DS-6. IRIS Data Services staff is organized within four tasks: (1) DMC Operations takes care of most of the data curation activities and interacts with the user community regarding data issues as well as remotely staffing the Auxiliary Data Center. (2) DMC Cyberinfrastructure supports the service interfaces and Web applications development, and generates and manages products. (3) Quality Assurance is responsible for software such as MUSTANG as well as working with data suppliers to improve the quality of the data managed at the DMC. (4) External Data Coordination works with domestic and international organizations including the FDSN, WDS, and the EarthCube Council of Data Facilities to establish and maintain data standards and facilitate free and open exchange of data.

Through these affiliations, IRIS ensures that its approach to data management is responsive to the Earth science community's needs and that we follow best practices in data management and curation, and reach communities beyond the geosciences, including the general public. IRIS will maintain its WDS membership, and pursue certification as a trusted digital repository and credentials as a Data Management Maturity Model, now being offered through the American Geophysical Union and other organizations.

Scientific community input on the technical capabilities and operation of the NGEO Data Management System, including both IRIS and UNAVCO components, will be provided by the joint IRIS/UNAVCO Data Services and Products Advisory Committee. Membership on the Data Services and Products Advisory Committee will be chosen from the broad geophysical community served by the NGEO Data Management System.

FRONTIER DATA SERVICES

Connecting Big Data to HPC and the "Cloud" – WBS 1.2.2

Seismology is a data-rich science, with researchers needing to access and process terabyte-scale data sets. It's computational demands can be met only by access to very high performance computing systems. In this frontier activity, IRIS and UNAVCO propose to (1) improve geosciences community access to HPC systems, and (2) provide systems that are designed to support very large amounts of observational data and address the emerging Big Data problem.

The Frontier Challenge

Two very different types of computer architectures are required to meet the computational needs of geoscientists. The traditional approach to solving HPC problems is to use highly optimized, parallelized code running on enterprise class supercomputers with a minimum number of I/O operations. An example from seismology that requires HPC infrastructure is the generation of three-dimensional synthetic seismograms at higher frequencies for massive global data sets. However, other problems in seismology fall into the class of what is being termed Big Data problems that tend to have a large number of I/O operations running on multiple cores. Big Data problems are not amenable to HPC environments but rather require many core systems configured and managed in a manner where non-parallel codes run on many independent cores simultaneously. An example of this type of problem is performing cross-correlations on millions of seismograms in the IRIS data collection, or running a suite of quality assurance metrics on large numbers of seismograms. Big Data environments are also elastic, where more cores can be temporarily assigned to a task as needed and then released for use by other processes. The capacity of the system expands and contracts elastically as computational requirements change. This elastic capability can exist in a cloud environment. Cloud environments are now becoming available in NSF-funded centers such as XSEDE and commercially. IRIS currently has a no-cost allocation in XSEDE for testing purposes and has requested a much larger allocation for the GeoSciCloud project.

The characteristics of these two classes of computing architectures are captured in **Table FHPC-1**. In the NGEO, HPC resources will be used by the geoscience community, whereas Big Data resources will be used by both the research community and the NGEO data centers for calculation of quality assurance metrics and other processing.

Proposed Activities

The National Research Council Committee on Seismology and Geodynamics recently stressed the need to enable "*much broader access to computational facilities over the coming years*" by community building through training and the development of teaching materials targeted toward the understanding of HPC and Big Data resources (Richard Allen, Chair of the Committee on Seismology and Geodynamics, *pers. comm.*, 2016). Additionally, they encouraged identification of liaisons that would help connect domain scientists with computational facilities.

A recent survey of more than 325 members of the worldwide geophysical community by IRIS's HPC Working Group showed strong support for improving community access to HPC resources. In fact, roughly 94% of respondents indicated that they either currently use HPC resources or plan to do so. However, 89% of the respondents do not use or make little use of computing resources that are specifically designed for Big Data problems confronting geophysics. Nearly three-quarters of the current users of HPC resources indicated that they would see moderate to great benefit from improved training in various HPC computing tasks. As part of this frontier activity, we will help our community move in this direction by:

- Developing data packaging methods that reduce the amount of I/O in HPC environments
- Offering a training course for our community that addresses accessing HPC and cloud resources
- Simplifying the process by which geoscientists can understand and make use of HPC to conduct their research
- Offering training courses in Data Science, including training in such tools as R, Python, and Jupyter notebooks

The NGEO can assist our community by making its data available to researchers in close proximity to HPC and cloud systems. The NGEO data centers do not anticipate using HPC resources for data center operations. However, we will collaborate with the Computational Infrastructure for Geodynamics at the University of California, Davis, to make HPC resources more accessible to the NGEO community. The CIG is a community-driven organization that advances Earth science by developing and disseminating modeling and other software for geophysics and related fields. Through an award from IRIS, the CIG will work with IRIS and UNAVCO on the following tasks:

- Provide training for geoscientists in data science to manage large data sets
- Provide training for geoscientists unfamiliar with HPC and cloud computing to be able to work in those environments
- Establish and maintain scientific workflows in HPC and cloud environments (using Jupyter notebooks or other appropriate tools)
- Provide a general user help desk for our communities to work in HPC and/or cloud environments

TABLE FHPC-1. This table captures the primary differences between HPC and Big Data requirements. IRIS proposes to provide access to both of these architectures in the NGEO Data Management System environment. *From Magaña-Zook (2016)*

	HPC	BIG DATA
Typical Use Case	CPU-bound problems	I/O-bound problems
Cost	\$500K (Cray XC30-AC) to \$390M (Tianhe-2)	~8K per node
Input vs. Output Size	Input << output	Input >> output
Programming Language	Fortran, C, C++ (at LLNL)	Java, Scala, R, Python, and more through streaming/piping
I/O	Transferred to compute node	Local to compute node
Network Backbone	Infiniband (up to 300 Gb/s with enhanced data rate & 12x port width)	Ethernet (typically 1 Gb/s or 10 Gb/s)
Fault Tolerance	Check-pointing	Recompute data slice

Workflows. Certain problems identified in the June 2014 white paper, "Advancing Solid Earth System Science Through High-Performance Computing" (Hwang et al., 2014), can be addressed by having all of the NGEO data managed centrally in the cloud. For HPC problems, CIG-vetted and maintained codes can be pre-installed on HPC and cloud systems. Data sets will be available over very high-speed interconnects between computers and storage resources. Workflows with user-defined parameters can be pre-installed and the effort needed to invoke many common workflows made much simpler. The details of installing, validating, and acquiring allocations will be minimized for researchers. We anticipate moving to Jupyter notebooks as a mechanism to share applications and workflows in this environment. This activity will be jointly developed and maintained by CIG, IRIS, and UNAVCO.

Real-Time Data. The NGEO Data Management System will ingest real-time data into a cloud environment to improve reliability and stability. These data will go into a system that can perform Big Data analytics. We will use DataTurbine or similar software to manage and buffer a wide range of streaming data formats, including those available from IRIS using the SeedLink protocol that supports real-time geophysical time series data, and the RTGNSS format that is being proposed by UNAVCO and others for geodetic data.

Resources. While the EarthCube GeoSciCloud project will provide funds for prototyping, IRIS and UNAVCO will work together with partners in XSEDE, and with federal agencies (e.g., DOE, NASA, USGS, NOAA) through other funded efforts, to marshal the required operational resources. XSEDE operates Jetstream, the NSF's first production cloud for science (Stewart et al., 2016). It consists of 640 nodes geographically dispersed into two 320-node systems. One node system is housed at Indiana University's Data Center; the second system is at the Texas Advanced Computing Center. Each 320-node system has 640 Intel Haswell CPUs with 7,680 cores, 40 GB of memory, 640 TB of local disk, and 960 TB of additional available storage. The two systems are connected to Internet2 via 100 Gbps links and via 10 Gbps links to XSEDE resources.

As noted in the 10-year plan for foundational NGEO data services, UNAVCO and IRIS intend to operate their Auxiliary Data Center in a cloud environment. We anticipate some costs savings from this shared infrastructure, and those savings will be applied to this frontier activity. The University of Indiana, a primary node within XSEDE, has provided a Letter of Collaboration for their participation in this frontier activity and in joint efforts to identify funding that will augment the funds included in the NGEO budget to support our operations in XSEDE. At the current time, IRIS has an allocation request to use XSEDE resources including 0.5 petabyte of storage and 1.2 million CPU hours. Costs for HPC and cloud computational infrastructure will be borne by XSEDE.

Education, Workforce Development, and Public Outreach – WBS 1.3

INTRODUCTION

IRIS and UNAVCO propose to use their combined expertise to create an NGEO Education, Workforce Development, and Outreach (EWO) program that will be a world leader in providing access to original data and interpreted results from seismology, geodesy, and other geophysical research; developing educational resources for a broad range of audiences; and providing access to, and instruction in, the use of geophysical techniques. The NGEO EWO program will also be at the forefront of geoscience education, workforce development, and outreach efforts, building on nearly 15 years of collaboration between the IRIS Educational and Public Outreach and the UNAVCO Education and Community Engagement programs. The goals of the NGEO EWO efforts, based on community recommendations in the "Futures" Facility Workshop Report (Aster and Simons, eds, 2015), are to:

- Produce innovative educational resources and technologies through the involvement of researchers, educators, and other experts and disseminate a full suite of EWO products to public audiences from grade 6 to adult, teachers, undergraduates, graduate students, early career professionals, and university faculty and researchers.
- Foster the development of a robust, well-trained, diverse geoscience workforce with the knowledge, skills, and abilities to tackle emerging scientific and societal issues.
- Engage the general public by highlighting the advances in, and societal relevance of, geophysical research, particularly with respect to natural hazards, water resources, and energy concerns.

Successful engagement of such a wide variety of stakeholders with varied knowledge and expertise requires staff and infrastructure to support a multitude of activities. To achieve the needed breadth, we propose an EWO program for the NGEO composed of complementary activities conducted by either UNAVCO or IRIS, with a subset of activities conducted jointly where clear synergies have been identified. IRIS and UNAVCO staff have both the scientific expertise to interpret technical information for broad audiences as well as the educational expertise to create resources and conduct training using research-based pedagogy and best practices.

IRIS and UNAVCO will organize their respective activities around the above common goals, and an agreed upon set of objectives with each organization leading efforts for particular activities based on their established strengths (Charlevoix et al., 2013; Taber et al., 2015). **Figure EWO-1** shows the division of responsibilities for education and workforce activities. IRIS and UNAVCO will also develop an integrated NGEO social media strategy, and jointly support early career professionals. The IRIS and UNAVCO programs have successfully collaborated on a range of activities in the past, including workshops, student field trips, lecture series, social media, early career events, development of museum displays, and intern program evaluations. We have coordinated activities nationally and internationally in partnership with other national geoscience, diversity-focused, and educational organizations, and we will work together to draw on existing and new relationships to allow us to leverage our efforts for greater impact.

Each organization will have a logic model (an established practice for identifying short- and long-term program outcomes based on available program resources), implementation plans, and evaluation strategies that will be complementary, but distinctly focused on each organization's areas of responsibility. For example, IRIS will lead grade 6–12 curriculum and professional development with UNAVCO involvement, while UNAVCO will lead undergraduate curriculum development with IRIS involvement. This framework provides clear lines of responsibility, ensuring accountability while providing enough flexibility to respond to new opportunities or requests from the community and sponsors.

In addition to our ongoing foundational activities, the NGEO facility is uniquely positioned to make a broad and systemic impact on increasing the diversity of students engaged in the geosciences through leveraging both facility expertise and the academic scientific community that are part of the IRIS and UNAVCO consortia. UNAVCO and IRIS are proposing an innovative frontier initiative in the NGEO that, when coupled with the foundational workforce support of each organization, will provide a coherent set of pathways to engage students from groups historically underrepresented in the geosciences.

IRIS Component of the NGEO Education, Workforce Development, and Outreach Program – WBS 1.3.1

The IRIS EPO program has brought unequaled access to geoscience information and interpreted seismic data to a wide range of audiences, from simple, easily accessible views of recent global seismicity that receive 24 million page views per year to real-time streaming of seismic data direct from the IRIS DMC to middle schools through college classrooms across the United States and around the world (**Table EWO-1**). Through its commitment to advance awareness and understanding of seismology and geophysics while inspiring careers in the Earth sciences, the IRIS EPO program has established itself as a model among NSF-funded programs with its focus on seismic data and seismology-related education across a wide range of audiences, providing analysis, visualization, and teaching tools and resources that aren't available elsewhere. Individual program elements are carefully chosen to couple closely to the science that is enabled by the facility, such as data-driven exercises about glacial earthquakes and climate change, induced seismicity, and deep Earth structure.

The IRIS EPO program has had significant impact in a

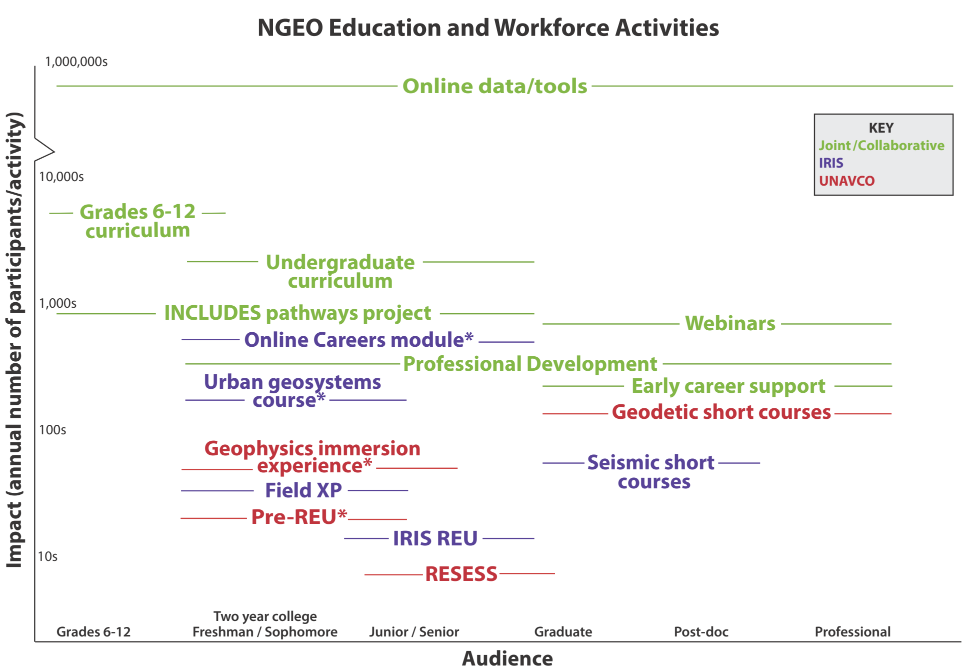


FIGURE EWO-1. The suite of workforce and diversity activities to be offered through the NGEO facility. * indicates a frontier activity.

TABLE EWO-1. Annual reach of selected IRIS EPO products and services.

ANNUAL AVERAGE	IRIS EPO PRODUCTS AND SERVICES WITH THE LARGEST ANNUAL REACH
24,000,000	Page views for the IRIS Seismic Monitor. Sixty percent of all IRIS Web visitors start at this site and 25% of visitors are Spanish speakers.
2,400,000	People reached via the IRIS EPO Facebook page. Nearly 90% of users report the page provides high-quality, trustworthy info, and good educational resources.
650,000	YouTube views of animations, videos, and webinars. The United States comprises 34% of viewers, followed by Ecuador, the UK, and Mexico.
372,000	Users of the IRIS Earthquake Browser.
76,000	Page views for the IRIS Teachable Moments website. Currently, there are over 3000 subscribers who receive notifications when new slide sets are released.
45,600	Users of Seismic Waves. Over 70% of geoscience educators anticipating using the tool with students.
20,400	Downloads of IRIS lesson plans and classroom demonstrations. 100% of teacher-trainers rate the quality of these resources as high or very high.
1100	Attendees of the IRIS Distinguished Lecture Series. All venues strongly agree or agree that the audience was engaged.

variety of areas, ranging from an educational resource repository with over 9000 downloads per month to contributing to the development of the Earth science workforce through a highly regarded and highly competitive summer research program for undergraduates. The sustained efforts of the program provide potential pathways for students to progress from middle school through to a career. For example, a student who was introduced to seismology via hands-on interaction with a middle school classroom IRIS seismograph went on to become an IRIS undergraduate intern and then a geophysics graduate student and is now working in industry. Past interns are now mentoring their own interns, and the community of early career scientists receives ongoing support and guidance as they enter and navigate the workforce.

IRIS EPO has built a reputation for quality resources: 90% of Facebook users (reaching 200,000 viewers per month) believe our page provides "high quality information that they can trust" and 100% of teacher-trainers rate the quality of IRIS's educational resources as high or very high, as also evidenced by the hundreds of teachers who flock to the IRIS booth at National Science Teachers Association meetings to find out about our newest software and Web tools, animations, and classroom activities. IRIS has helped lead the use of active learning and data in the classroom and is now well positioned for our curriculum materials to be adapted to satisfy Next Generation Science Standards (NRC, 2013b) criteria. We are continually asked to share our resources, particularly our animations, for use in other organizations' middle school through undergraduate educational products, such as the set of 45 IRIS animations now part of the online resources for Stephen Marshak's *Essentials of Geology* textbook.

While much of our effort is now focused on online dissemination of resources, informal geophysical science opportunities at museums, public science events, and public lectures help to reach an audience that might not be introduced to geoscience online, and also help to raise the public profile of geoscience. We also work to engage additional audiences through our Spanish language materials, such as our Spanish language event lists, which are the second-most visited pages on the IRIS website after the Seismic Monitor, with over 1.2 million views per year.

Description and Capabilities of the IRIS Component of the EWO Program

The IRIS EPO program has been developed in response to the NSF's strong emphasis on the integration of research and education (NSF, 2014), and to address particular audiences so that they can contribute to critical geoscience-related societal needs (AGI, 2016). The resulting capabilities allow us to positively impact teaching of geoscience at the middle school and high school levels where most Americans receive their only formal geoscience education, by assisting in the development of the future geoscience workforce at the undergraduate through early career stages, and expanding the general public's awareness of geoscience-related issues so that they can make informed decisions. Here, we describe successful ongoing IRIS seismology-focused EWO activities that we propose to continue in the NGEO, all of which are continually assessed via internal and external evaluation as described on page 70.

Summer Internships for Undergraduates in Seismology. Since its inception in 1998, the IRIS Undergraduate Internship Program, with support from NSF's Research Experiences for Undergraduates program, has provided 182 students with the opportunity to work with leaders in seismological research and to produce research products worthy of presentation at large professional conferences. IRIS provides centralized support for both students and mentors, but the program takes advantage of the Consortium's distributed yet extensive host pool to expose the undergraduate interns to research opportunities across the full spectrum of seismology. Although students conduct research at different IRIS member institutions, program activities have enabled each summer's cohort to successfully bond (Hubenthal and Judge, 2013). Mentoring is a critical component of the program and involves both a near-peer intern alumni mentor and structured support from research mentors. A research experience has been shown to be a key element in the selection of a career (Daniels et al, 2016), and based on long-term tracking of intern alumni, we find that over 80% of our interns go on to geoscience careers (**Figure EWO-2**). We propose to continue to jointly fund this program through the NSF REU program and through the NGEO, with REU funding supporting student costs, and with the NGEO funding infrastructure and oversight costs.

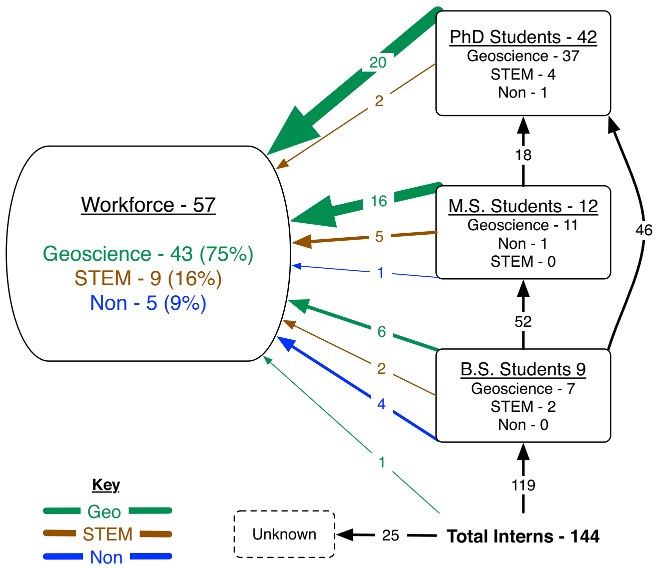


FIGURE EWO-2. Alumni career paths post IRIS internship. From 1998 to 2013, the IRIS Undergraduate Internship Program facilitated opportunities for 144 undergraduates. Solid lines indicate pathways, labeled with the number of interns who completed that pathway, and boxes indicate the number of interns in that stage of their career (e.g., 46 alumni completed undergraduate degrees and enrolled directly into a PhD program, while nine alumni are earning their bachelor's degree). Of those alumni in a geoscience career, the majority are split between careers in the energy sector (53%) and employment in academia and federal and state governments (44%).

Seismic Data and Earthquake Information in the Classroom. Calls for increased use of data in the classroom (PCAST, 2012) require easy access to data and intuitive analysis tools. Based on over 10 years of experience of supporting educational seismometers and providing data to schools, IRIS connects classrooms to high-quality, real-time seismic data and encourages students to interact with the data by providing recording and analysis software that supports local sensors or data streamed from a remote source. This allows IRIS to focus on providing online resources for accessing and sharing data and coordinating local and regional support efforts for teachers. Primary applications include the IRIS Earthquake Browser (**Figure EWO-3**) and jAmaSeis, a cross-platform software package that enables students to access real-time earthquake waveform data from either a local or remote educational seismometer or from any station streaming data to IRIS. Students can watch as seismic waves are recorded on their computer and can use the data to locate earthquakes and calculate magnitudes. Using this software, the NGEO will have an unprecedented opportunity to be involved in the dissemination of seismic data from Mars for educational and research use as part of NASA's Mars InSight mission, with data transmission starting in early 2019.

Newsworthy earthquakes capture the attention and imagination of students. In the classroom, this increased attention manifests as a "teachable moment" to increase students' understanding of both a specific event and seismology concepts more broadly. IRIS, in collaboration with the University of Portland, fulfills this opportunity by producing a rapid response resource in both English and Spanish following newsworthy earthquakes. IRIS Teachable Moments, with over 3000 subscribers, provide interpreted USGS tectonic maps and summaries, animations, visualizations, and other event-specific information for middle school through college educators to explore the unique storyline of a newsworthy earthquake with their students.

Curriculum and Professional Development. To increase the quantity and enhance the quality of seismology education, IRIS creates a spectrum of high-quality educational resources for educators and enables their use by making them easily accessible online and by providing instructors with the support necessary to effectively use the resources. Inquiry-based learning activities are geared toward middle and high school classrooms cover a wide range of seismological topics and make use of actual data and/or require students to collect their own data. At the undergraduate level, a suite of inquiry-based laboratory activities developed in collaboration with The College of New Jersey make the grand challenges of modern seismology accessible to undergraduates in 100- and 200-level courses. A set of lectures and exercises that introduce students to the basics of industry-related seismic processing and interpretation are also in the collection (Schroeder, 2015).

To expand the use of our curriculum resources, IRIS offers a variety of professional development opportunities for instructors at the undergraduate, high school, and middle school levels. Each workshop is designed to improve instructors' seismology content knowledge and pedagogy to enable instructors to easily employ IRIS resources in the classroom. Professional development opportunities range from one-hour sessions at regional and national conferences to multiday, customized workshops designed to meet the needs of a specific educational institution. In the NGEO, we will

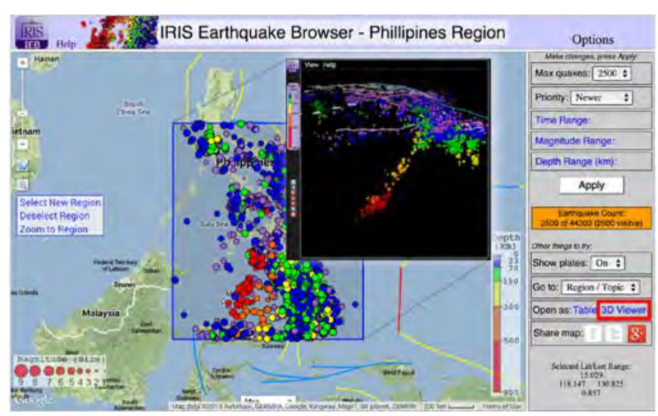


FIGURE EWO-3. The IRIS Earthquake Browser is an easy-to-use, interactive map that allows educational users and the general public to explore recent and historical global seismicity and tectonic plate boundaries. Up to 5000 quakes can be displayed at a time using various filtering criteria such as time, magnitude, geographic location, and depth. Alternatively, users can rotate and zoom through hypocenters using the 3-D viewer.

place increased emphasis on facilitating faculty professional development, particularly instructors at two-year colleges. Annually, over 800 teachers and college faculty, who reach at least 40,000 students, attend IRIS-led workshops. One year after participating in an IRIS professional development workshop, teachers in grades 6–12 report increased confidence in teaching seismology content, and 76% report they spend more time teaching seismology to their students.

Public Displays and Lectures. Informal science venues remain an important mechanism to reach different segments of the general public, and the display of real-time data offers the opportunity to capitalize on visitors' enthusiasm for current information. IRIS has experience developing public displays at scales ranging from single kiosks to complete exhibits (Smith et al., 2006; Taber et al., 2015), and currently helps maintain or has advised on displays in over 35 museums and visitor centers, including the Smithsonian Institution National Museum of Natural History in Washington, DC, and the American Museum of Natural History in NYC, and over 30 additional locations are using IRIS display software. There is also strong demand from science museums and science cafés to provide local communities with direct contact with distinguished scientists who can convey the excitement and the complexities of seismology to general audiences. We address such needs through our ongoing Distinguished Lecturer collaboration with the Seismological Society of America.

Plans for the EWO Program Over the Next 10 Years

An overarching goal of the NGEO EWO program is to help create a diverse future geoscience workforce, and a public capable of making informed geoscience–related decisions. The portfolio of educational, geo-workforce support, and outreach materials provides infrastructure to train and assist the next generation of geoscientists. Even with the recent downturn in the oil and gas industry, current projections show a shortage of 90,000 geoscientists over the next decade (Wilson, 2016). In order to achieve this goal, we will build upon our proven foundational programs and develop a Geoscience Workforce Initiative that includes both foundational and frontier elements, including an online module for geoscience career education and a new urban geosystems course.

Workforce Development. Geoscience lags behind most other STEM disciplines with respect to diversity, and future projections show no change in this situation in the coming years (Gonzales and Keane, 2010; NRC 2011a; NSF/NCSES, 2015). To confront this challenge, we propose an NGEO Geoscience Workforce Initiative that will provide resources and information to engage and retain a diverse community of students throughout their academic studies (grade 6 through graduate school) and into the early stages of their professional careers. IRIS and UNAVCO's experiences facilitating both large- and small-scale diversity programs create a unique platform on which to build a pathway of interconnected opportunities using a model of Engagement, Capacity, and Continuity (Jolly et al., 2004) as a strategy to aid historically underrepresented students in successfully pursuing paths to science careers. Our proposed activities will help fill critical gaps in the pathways available to students, by engaging students earlier through introductions to the geophysics of societally relevant issues, by providing research and professional development opportunities throughout their undergraduate years, and continuing to provide support structures in graduate school and into their careers.

The key stages of our proposed diverse workforce pathway are:

1. Grade 6–12 – Engagement. IRIS will continue to develop activities and link to pedagogically sound learning sequences that are aligned with the Next Generation Science Standards (NRC, 2013b) via a specially designed database and user interface. This educational product promotes linkages among resources that already draw over 20,000 downloads of lesson plans and classroom demonstrations annually. As technologies evolve and emerge, the EWO program will increase efficiencies even further, focusing on virtual and online training and dissemination of resources, including full online courses for teachers.

In addition, we will leverage resources and linkages to be created via a new NSF INCLUDES project called Engaging Local Communities in Geoscience Pathways. IRIS and UNAVCO are two of the partners in this multi-institution effort, led by Carleton College's Science Education Resource Center (SERC), to create pathways in three regional pilots that will be used as laboratories and catalysts for a systemic increase in diversity in geoscience and geoscience education. Built into the INCLUDES project are support structures for the transition from secondary to higher education, including coordination with community colleges.

2. Undergraduate – Engagement, Capacity, Continuity. We will engage and nurture undergraduates through a set of activities that will introduce geoscience to a broader range of students and highlight the possibilities of a geoscience major and career. Freshman and sophomores can take part in the IRIS FieldXP program, which introduces students to geophysical research opportunities at minority-serving institutions, by involving them as field assistants for a geophysics field experiment before they have enough physics/math to engage in a summer-long research project (**Figure EWO-4**)

More senior students will be encouraged to participate in the IRIS REU (Hubenthal and Taber, 2014) and UNAVCO's RESESS program (Charlevoix and Morris, 2014), both long-established opportunities to broaden participation in geosciences. To recruit students, IRIS and UNAVCO take advantage of their long-term relationships with minority-serving institutions and also their special joint minority alumni speaker series.

FIGURE EWO-4. The FieldXP program capitalizes on the potentially catalytic nature of short-duration field experiences to increase math, physics, and computer science students' awareness of the field of geophysics and encourage them to consider the field as a career path. Here, students and postdocs, including two FieldXP students, gather for an evening lecture during the 2016 Wavefields experiment (see sidebar on page 46).

Students will also be introduced to geoscience research and careers through increased association with the Society for Advancement of Chicanos and Native Americans in Science (SACNAS), where IRIS and UNAVCO have jointly run a student field trip at the annual meeting over the past 10 years. We will also increase our involvement with the National Association of Black Geoscientists and the National Society of Black Physicists.

These activities will help encourage a more diverse group of students to engage in geoscience as undergraduates, and can act as a base upon which to develop the much larger scale frontier diversity activities.

3. Graduate and Beyond – Continuity. To learn about career options and paths for graduate school, students near the end of their undergraduate experience, will be able to access resources through the NGEO, as well as complementary resources available through other geoscience organizations. Students will also be supported through the cohorts developed during REU and earlier experiences that will be part of the NGEO pathway. After students transition to graduate school, the early career program described below will provide support through graduate school and into professional careers, as will training courses in seismic techniques and computational methods. These materials will also enable graduate researchers from smaller institutions to enhance their range of analytical tools beyond what is locally available.

IRIS recognizes that development of classroom resources requires a major investment of time by early career faculty. The community has expressed a need for a range of advanced-level resources in geophysics and related topics, such as graduate-level seismology or geodynamics. In coordination with SERC, IRIS will create a course repository of advanced seismology and geophysics course materials to encourage sharing and dissemination of established courses among interested faculty. Through virtual communities, workshops, and meetings, IRIS will also serve as a matchmaker between geophysicists and geoscience, physics, and math-based education researchers, teachers, and geophysicists, to build and disseminate best practices in teaching geophysical concepts, and to invigorate investigation into effective geophysics pedagogy.

Early Career Support. Early career geoscientists face many challenges as they transition from graduate students into postdoctoral fellowships and pre-tenure faculty positions, or to the vast array of employment opportunities outside of academia. However, many receive little mentoring or guidance on how to successfully make the leap from graduate school and move their career forward, especially in careers outside of academia. In recognition of these challenges, IRIS created an Early Career Investigator Program (Colella et al., 2015).

While in the past some IRIS and UNAVCO early career activities have been independent, future planning and implementation will be joint in order to nurture a larger and more diverse group. We will focus on mentorship opportunities, building virtual and in-person communities of geoscientists from a range of backgrounds, workshops, and meeting events. Planned activities will leverage programs led by other groups such as the National Association of Geoscience Teachers and the Geological Society of America, and will include developing an NGEO Early Career Investigator website and Facebook presence that will replace and build on the existing separate platforms. Virtual communities, training and webinars, and communal sharing of resources can significantly increase the research and collaboration opportunities for early career investigators from smaller or more resource-limited departments. Additionally, webinars and social media interactions will explore career topics; best practices in mentoring, teaching, and research; disseminating new research methods; interaction with the public and media; and exploring ways to reduce barriers to success for geophysicists from nonmajority backgrounds.

Animations, Simulations, Videos, and Visualizations. The seismology topics covered in the workforce programs described previously can be difficult to convey through text or images alone, which has led IRIS to develop a suite of over 100 animations that illustrate fundamental seismology concepts. These clips range from a few seconds to several minutes in length, and cover both basic seismology-related topics and more complex concepts, such as focal mechanisms. As a result of the concise format and their dynamic nature, there have been over 2.7 million views of IRIS animations through our YouTube channel alone.

Working with IRIS Data Services, we propose to expand beyond animations and visualizations to interactive seismology simulations, allowing more effective inquiry-based learning from sixth grade through professional levels. Simulations have been shown to increase student learning and engagement in geoscience (Lant et al., 2016; Luo et al., 2016) as well as in physics (Wieman et al., 2008) and can result in better student performance than physical laboratory exercises (Pyatt and Sims, 2012) due to students taking ownership of their exploration and drawing their own conclusions about the effects of different variables (Podolefsky et al., 2013). These simulations will help educators integrate authentic research experiences into their course curricula.

To further expand our online audience, IRIS will also explore the category of advanced informal video education on seismology and shallow geophysics topics, following the success of YouTube video sites like "Numberphile," which presents theoretical math to an educated non-expert audience, and where views can number in the tens of millions.

Social Media and Citizen Science. To reach a broad audience, including the growing portion of the population who get their news via social media, IRIS and UNAVCO will develop an integrated social media presence for the NGEO that will include shared and independent channels. This will allow us to reach specific scientific communities with relevant information and leverage our resources. Each organization will continue to maintain a limited number of channels specific to the geodetic and seismological communities, while contributing relevant content to broader audiences via NGEO social media feeds. We will rigorously evaluate the impact of all NGEO social media platforms using online metrics and will annually survey users to assess the effectiveness of the current social media, implementing changes as needed based on the survey results.

One of the NSF's goals is to promote public and community-based science that can be addressed through the growing public interest in citizen science projects. We propose to develop a national-scale citizen science program through ongoing collaborations with the Southern California Earthquake Center, building on the solid foundation of the thousands of sensors in the Quake Catcher Network (QCN) (Cochran et al., 2009). QCN will engage the public via interactive, mobile-friendly software that will illustrate how to collect and share ground-motion recordings. QCN sensors are easy to deploy and their low cost allows for the deployment of hundreds in areas of known earthquake hazard and in response to a major earthquake (Cochran et al., 2011), and ground-motion data have proven useful in the creation of ShakeMaps (Dominguez et al., 2015). As the technology continues to evolve, we will also explore collaboration with other groups such as Berkeley's MyShake earthquake early warning system that uses cell phones as the primary recording device.

Management and Organization

The IRIS Education and Public Outreach and UNAVCO Education and Community Engagement directors will each lead their components of the integrated NGEO EWO. This structure will leverage unique skills and strengths in each organization and avoid duplication of effort. A joint IRIS/UNAVCO Education, Workforce, and Outreach Advisory Committee will provide community guidance for the combined EWO program. The IRIS and UNAVCO program directors will develop complementary implementation plans that will inform the annual scope of work and individual projects for each organization, with some projects such as social media and support of early career professionals handled jointly. The program directors will meet monthly (virtually) to coordinate work effort and management of projects with an additional monthly joint (virtual) meeting of all EWO staff.

FRONTIER EWO PROGRAMS

Workforce and Diversity Initiative – WBS 1.3.2

The "Futures" Facility Workshop Report highlighted the need for effective and evidence-based strategies to engage a diverse student population for the nation to remain a leader in the geosciences (Aster and Simons, eds, 2015; p. 41). Most diversity programs have sought to prepare upper-level undergraduates for graduate careers in geoscience through the development of their own capacity (through instruction and training) and by building connections to a community of like-minded individuals. Examples include UNAVCO's RESESS Program (Charlevoix and Morris, 2014) and Penn State's Africa Array program. Collectively, these programs and others from outside the geosciences have demonstrated that recruiting underrepresented minorities and other underrepresented groups into the geosciences is possible, but only through the long-term commitment of both time and funding (Prendeville and Elthon, 2001).

The Frontier Challenge

While successful diversity programs have been established, including UNAVCO's RESESS internship program (Charlevoix and Morris, 2014), several issues exist in the overall landscape of solid Earth geoscience diversity programs. First, the total number of slots for minority students to participate in these programs is quite small. Second, gaps in opportunities exist at the undergraduate freshman and sophomore levels, a critical juncture in a student's choice of a major. Finally, the magnitude of the effort to fund and run such programs over long periods of time has created a patchwork of diversity initiatives with different organizations each running highly targeted programs often in isolation. Further, these programs tend to be funded on short-term (e.g., three-year) cycles. Combined, these factors make it difficult for students to learn about opportunities and then participate in a way that turns the patchwork into their own coherent pathway (NRC, 2013a).

The NGEO facility is well positioned to make a broad and systemic impact on diversity within the solid Earth geosciences. Both IRIS and UNAVCO have considerable expertise working to enhance diversity within the solid Earth geosciences, and they have strong connections with the academic community at a variety of post-secondary institutions, including four-year research institutions, liberal arts intuitions, minority-serving institutions, and community colleges. They also have the staffing capacity to run multiple integrated diversity programs simultaneously and effectively.

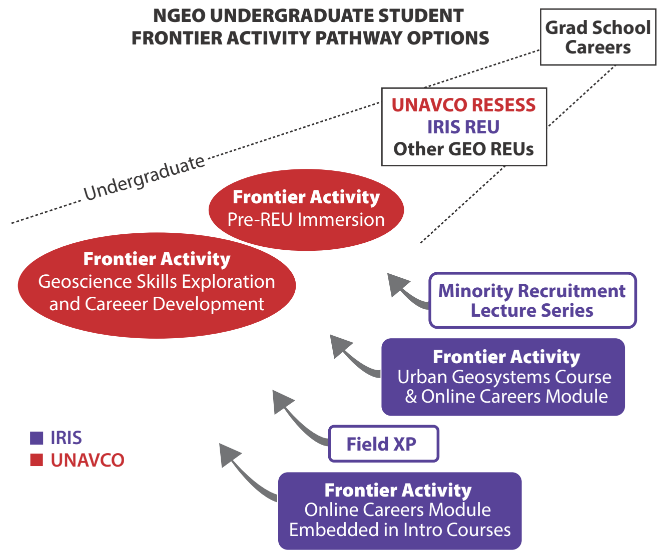


FIGURE EWO-FR1. Alignment of NGEO undergraduate student activities. IRIS's frontier activities (white text on purple) actively engage and recruit underrepresented minority students into the geosciences. UNAVCO's frontier activities (white text on red) prepare and maintain students (rising sophomores and juniors) in the geoscience career pipeline through multiweek residential training programs. Both are supplemented and complemented by IRIS's and UNAVCO's foundational activities (text on white) such as summer research programs (REU and RESESS), the Minority Recruitment Lecture Series, and the FieldXP program.

Proposed Work

IRIS and UNAVCO propose a new joint Workforce and Diversity initiative to address the engagement and recruitment of underrepresented groups in the geosciences. When coupled with the foundational workforce activities proposed by IRIS and UNAVCO, we will provide a set of interconnected programs that students can enter into and depend upon as they navigate their career pathway (**Figure EWO-FR1**). UNAVCO will focus on developing student skills and retaining them in geoscience via a one-week summer geoscience skills exploration for incoming freshman and sophomores and a three-week summer experience for older students not yet ready for a full summer of research. IRIS, working with the new Near-Surface Geophysics Facility at the University of Wyoming, proposes to develop two frontier activities to attract and engage students from underrepresented groups to pursue a geoscience career.

Urban Geosystems Course for Freshman or Sophomores. We propose to develop a new half-semester-long place/problem-based course to engage freshman and sophomores in questions or problems in their communities that can be addressed with geophysical approaches, and that will leverage field equipment and training expertise available via the new Near-Surface Geophysics Facility. The societal issues this course will address include a range of natural and human-induced hazards related to the sedimentary basins upon which many cities are built. Issues might include contamination and sustainability of groundwater, basin subsidence, and earthquake site response or vulnerability to other hazards such as landslides or flooding. This course will be designed so it can be taught by geoscience or physics faculty from two-year colleges through research universities. The goals of the course are to (1) recruit a diverse student population to enroll, (2) engage students in hands-on/minds-on learning of geoscience content and research skills, particularly an introduction to data-intensive computational techniques, and (3) overcome the perception of a lack of societal relevance of a geoscience career. Positive experiences in quality introductory geology courses have led many students to enroll as geoscience majors (e.g., Houlton, 2010; Stokes et al., 2015), and classroom research projects have been suggested as a way to increase diversity in the geosciences (Baber et al., 2010). Courses based on locations of cultural interest to minority students have been shown to be effective in attracting and retaining minority students (Hammersley et al., 2012). This activity also addresses an NSF Geosciences Directorate frontier theme, urban geosystem science (NSF Advisory Committee for Geosciences, 2014).

IRIS is ideally suited to lead this effort because of its experience in developing interactive curricula via the SERC InTeGrate project, its close collaboration with the NSGF, and the connection to Consortium member faculty. To plan the course, IRIS, the Near-Surface Geophysics Facility, and faculty from Rutgers-Newark University, a highly diverse research institution with a track record for attracting minority students to geoscience, will host a workshop for geophysics, geoscience, and physics faculty from minority-serving institutions. The workshop will emphasize the development of examples of questions/problems that would engage students. Topics could include hazards, energy, and the environment, and other urban geoscience concerns. Following a process developed by InTeGrate (Steer et al., in review), three faculty from different institutions will develop course materials, under the guidance of NGEO staff, that use geophysical data sets and optionally include use of geophysics instrumentation to address such urban issues. The course will then be piloted at the developer-faculty campuses, revised based on feedback from the pilots, and published and promoted in collaboration with SERC.

The course will focus on active use of data and introductory research, following the recommendation of the President's Council of Advisors on Science, Technology, Engineering and Mathematics (PCAST, 2012). While active use of equipment in the field will be an element of the course, the course will use a modular design to allow faculty to choose which, if any, equipment they want to use and in what order. This will allow the course to be run in the classroom using only provided or online data sets and will also allow modules from the course to be used as part of other existing courses. An important component of the course will focus on developing students' computational skills and introducing them to career opportunities associated with processing and interpreting large geoscience data sets so as to highlight that not all geoscience careers are field based.

The initial target audience for teaching the course will be faculty at minority-serving institutions that are IRIS members or have an interest in near-surface geophysics. This group of instructors will be expanded to geoscience and geophysics faculty who want to increase their use of geophysics to engage minority students. Given this audience, a key component will be to train faculty who are teaching the course in the use of field equipment to be loaned to the participating institution and provided by the NSGF, and to introduce them to data processing and associated computational skills needed to process and interpret the data collected in the field. The NSGF will be involved in the development of the course as well as training workshops to be held annually at the NSGF for faculty interested in using shallow geophysics equipment for educational purposes. Faculty teaching the course will be able to request the equipment from the NSGF, and shipping will be covered for minority-serving institutions.

Online Module for Geoscience Career Education. Student perceptions of the prestige of a field of science have been shown to be a significant factor in selection of a major. Unfortunately, underrepresented minority students tend to perceive geoscience poorly in terms of salary potential and as one of the least prestigious of the sciences partly because of its reliance on fieldwork (Hoisch and Bowie, 2010; Sherman-Morris and McNeal, 2016). To address this issue, Sherman-Morris and McNeal (2016) recommend that "Geoscience elective courses and information used to recruit students into those courses should address career pathways, salaries, workforce needs, and highlight technological aspects of the geosciences and opportunities in the laboratory, as well as make evident how the field contributes to society and the environment." Currently, individual faculty must independently identify relevant information and develop instruction that effectively incorporates the information into their classrooms. The effort involved may discourage many faculty members from acting on this recommendation.

To reduce this effort, IRIS will develop a free, asynchronous, online geoscience careers module that will be designed for use in any introductory geoscience course, with particular emphasis on two-year community colleges. The primary goal of this module is to increase minority interest in geoscience by establishing the societal relevance of the field, and showing that geophysics jobs help local communities, do not necessarily require fieldwork, are in demand, and are well paid. IRIS will collaborate on the active learning module design with the American Geosciences Institute, which regularly conducts research and analysis of career paths in the geoscience workforce. The module will be constructed using edX, an open-source, nonprofit online platform designed to provide access to high-quality education for everyone. The module design will recognize learning as an active process requiring minds-on engagement (NRC, 2000). We will also partner with UNAVCO to leverage their expertise and pre-existing video resources such as career profiles.

While the online module will be designed, tested, and originally implemented as part of the Urban Geosystems course, the target audience is much broader. IRIS will develop an instructor guide to allow any faculty teaching an introductory geoscience course to implement the online module. The online nature of the module will enable wide distribution. The module and guide will be promoted through workshops at geoscience professional meetings and through the American Geosciences Institute, the National Association of Geoscience Teachers, and SERC, as well as via workshops at geoscience professional meetings.

Contributions to Diversity and Workforce Development

In addition to the formal diversity and workforce development programs described above, diversity and workforce development are integrated into all IRIS activities in the NGEO. New Mexico Tech, which hosts the PASSCAL Instrument Center, is a Hispanic-serving institution with a strong focus on STEM education. This provides a diverse pool of science and engineering students for hiring at the facility. The PIC and New Mexico Tech support the summer IRIS Undergraduate Internship Program by hosting the orientation week activities for the students, and by providing both facility support and NMT faculty/staff for training in seismological techniques both in the field and in the classroom. The PIC also offers a nationally competitive graduate-level summer internship each year that provides field, instrument, and data analysis training to students.

PASSCAL contributes to workforce development by providing pre-experiment training at the PIC and, in some cases, in-field support for students and PIs from across the seismological community. PASSCAL also supplies equipment for educational uses at IRIS member home institutions. These activities have helped lower the barriers associated with access to instrumentation and have increased the diversity of facility users. For example, over the past 15 years, there has been a threefold increase in the number of female PIs on PASSCAL experiments.

The Near-Surface Geophysics Facility will provide unique opportunities for engaging students from diverse backgrounds, complementing the Urban Geosystems course. Techniques used by the NSGF can connect students with visible surface geology, addressing issues of immediate societal relevance such as availability of groundwater resources or urban planning. Modern instruments are easy to operate, enabling field success by inexperienced students. Data collection is also less expensive than many other geophysical techniques, making it more accessible to small schools. Finally, near-surface geophysics skills are valued in the geotechnical, groundwater, and environmental consulting industries, attracting students who are looking for marketable job skills. The NSGF will help broaden and deepen such experiences by: (1) leading workshops and summer field courses, (2) creating online resources for teaching/labs in near-surface geophysics, (3) supporting a public database for near-surface geophysical data, and (4) providing equipment support for primarily undergraduate institutions and their classes.

IRIS has a long record of building capacity in the international geoscience community. The GSN and PASSCAL work closely with international researchers and their students, postdocs, and technical staff, sharing scientific knowledge and technical expertise across many different cultures and countries. For example, GSN engineers provide training on seismic network installation techniques and on operations to local station hosts in countries around the world. This outreach not only improves GSN data quality, but facilitates the exchange of accumulated technical knowledge about the most efficient methods of operating high-quality seismic networks in remote locations. International researchers and their students often participate in PASSCAL and polar field programs where the knowledge they gain from U.S. researchers and IRIS staff contribute to international capacity building.

IRIS Data Services contributes to diversity and workforce development primarily through training activities, including short courses held in conjunction with national conferences such as the annual fall meeting of the American Geophysical Union or biennial IRIS workshops. IRIS regularly holds international data workshops where training is provided on the management of metadata and time-series data from seismological networks. The goal of these workshops, usually held in developing countries in Asia, South America, and Africa, is to enable open data sharing and exchange of ideas with the broader global seismological community. This international capacity building has played a major role in opening access to seismological data, greatly increasing data coverage worldwide.

IRIS and its subawardees value diversity and are committed to attracting, retaining, and promoting women and underrepresented ethnic groups in their organizations and in the IRIS governance structure. Fifteen of IRIS's 65 employees list themselves as African American, Asian, Hispanic, or American Indian/Alaska Native, and 40% of IRIS's staff are women. At the PASSCAL facility, 10 of its 34 employees are Hispanic, Asian, or African American, and 38% of its employees are women. IRIS's community governance structure provides unique opportunities for a diverse population of early and mid-career scientists to develop leadership skills and learn about the broader scientific enterprise.

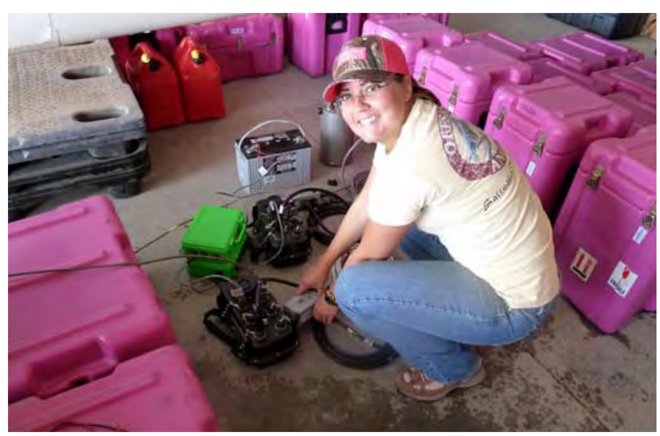


FIGURE DWD-1. Testing portable instruments at the PASSCAL Instrument Center at New Mexico Tech.

Risk Management

Risk management is a key part of IRIS's successful project management and review process. A risk is any event that could prevent the project from progressing as planned, or from successful performance and/or completion. Risk can be an inherent and necessary part of making state-of-the-art seismological observations—for example, placing a seismometer in a location where it may be destroyed in order to capture a unique signal. But many other risks can be managed through a combination of management awareness and best practices.

Each IRIS facility manager has overall responsibility for managing project risk within the activities they manage. Risks are evaluated throughout all phases of projects, with the intent of identifying risks and mitigation strategies early, and raising the awareness of the project team regarding identification, communication, and mitigation of risks. New projects are typically started with a project charter, which explicitly identifies key risks and their mitigation strategies. Risks are also identified during the project life cycle, with larger projects maintaining a risk register. **Table RM-1** summarizes the general and project-specific risks for the NGEO, their mitigation strategies, probability of occurrence, and the post-mitigation impact (on a low, medium, high scale).

TABLE RM-1. IRIS project-specific risks. P = Probability. I = Impact. H = High. M = Medium. L = Low.

RISK	P	I	MITIGATION STRATEGY
All			
NSF funding less than proposed	M	H	Scope will be adjusted in consultation with the scientific community and the NSF to reflect budget limitations.
Non-performance by subawardees	L	M	Regular and continuous oversight by IRIS facility managers; if non-performance is not addressed, IRIS can rebid the work and choose another subawardee.
Loss of key personnel	M	H	Cross-training of staff; extensive documentation of operational tasks; key positions are included in IRIS succession planning policy.
Personnel Safety	L	H	IRIS will comply with all applicable health and safety laws and require its subawardees to do likewise. Employees are required to be conscientious about workplace safety and recognize dangerous conditions or hazards. IRIS provides specialized safety training for employees who are subject to unusual risks.
1.1.1 GSN			
Instrument obsolescence	H	H	Functional specifications for a new VBB vault sensor to replace the STS-1 have been established and we will work with vendors to develop this sensor. At selected vault installations VBB sensors may be placed in shallow boreholes to enhance performance. New instrumentation is extensively tested before deployment and there is regular technical interchange between operators.
Network outages or other communication failures	L	H	Two separate and independent data collection centers provide multiple data-flow paths and mitigates against a complete real-time network outage.
Economic or political factors that could impact operations and open, real-time access to data	M	L	Regular review of current Memoranda of Understanding with partner organizations and countries. Maintain good lines of communication through meetings at international scientific conferences. Network changes must consider potential impacts on international partners, earthquake monitoring organizations, tsunami warning centers, and nuclear test monitoring.
1.1.2 PASSCAL			
Instrument obsolescence	H	H	Completed comprehensive sustainability analysis of instruments in the pool. Plans in place for modernizing the instrument pool through a phased procurement and/or lease of replacement instruments using NGEO and non-NGEO funds. The phased approach provides flexibility to respond to community needs and take advantage of new, more capable instrumentation.
Equipment failures or performance issues	M	M	Statistics on equipment availability, failure modes, usage trends, instrumentation requests, and schedule delays are collected. Post-experiment out-briefings will be held to collect information from PIs on facility performance and how to make experiments more successful.
1.1.3 Polar			
Instrument loss and obsolescence	H	H	The extreme polar environment can be especially detrimental to equipment. IRIS will continue to work with manufacturers to develop instrumentation more suitable for work in polar regions, and will acquire that instrumentation, using both NGEO and non-NGEO funds (e.g., NSF MRI program).
Equipment failures or performance issues	M	M	Statistics on equipment availability, usage trends, instrumentation requests, data completeness, and schedule delays are collected for PASSCAL. Post-experiment out-briefings will be held to collect information from PIs on facility performance and how to make experiments more successful.

Continued next page…

TABLE RM-1. Continued…

RISK	P	I	MITIGATION STRATEGY
1.1.4 Magnetotellurics			
Transition from OSU to NMT operations experiences problems	L	M	The transition between subawards will be carefully structured and paced. A working group of stakeholders composed of management and technical staff from IRIS, NMT, and OSU will oversee the progress of various elements of the transition, meeting regularly to measure progress against the formal transition plan.
Performance of new long-period or wide-band instruments does not meet requirements	M	H	Risk will be managed through test and evaluation of candidate technologies, working closely with vendors. Small quantities of instruments will be procured initially to ensure the vendor(s) can successfully manufacture the product and meet community requirements. Test deployments using trial systems will be conducted by community members prior to any larger procurement.
1.1.5 Near-Surface Geophysics Facility			
Inadequate number of instruments in pool to meet user demand	M	M	Money has been budgeted to acquire additional near-surface geophysical equipment in the first and sixth years of the NGEO.
NSGF is not aligned with users needs and expectations	L	H	In the pre-award stage, we will conduct a user survey to identify user needs and expectations. Post-experiment out-briefings will be held to collect information from PIs on facility performance. A Near-Surface Geophysics Standing Committee will provide regular community input on facility operations and management and an independent, external review of the facility will be held in Year 4 of the NGEO.
1.1.6 Next Generation Geophysical Instrumentation			
Performance of new instruments does not meet requirements	M	H	Risk will be managed through test and evaluation of candidate technologies, working closely with vendors. Small quantities of instruments will be procured initially to ensure the vendor(s) can successfully manufacture the product and meet community requirements in actual deployments. Test deployments using trial systems will be conducted by community members prior to any larger procurement.
Import/export restrictions	M	M	International technology and communications import/export restrictions will be researched and documented, and strategies for addressing them will be prepared in advance to ensure the maximum capability can be legally and effectively deployed in various high likelihood regions of the world.
1.1.7 Seismo-Geodetic Seafloor Instrumentation			
Newly developed instrumentation may not meet performance requirements	M	H	Risk will be managed through utilization of systems engineering best practices, tailored for our needs. We will test and validate candidate technology at the subsystem and system levels. We will incorporate realistic lab and field tests to validate performance.
Reliance on single concept	L	M	We will make judicious use of subawards for developing competing solutions, with subsequent down-selection, where warranted and/or necessary.
1.2.1 Data Services			
Natural disaster or local hazards	L	H	All key DMC systems are replicated at an unmanned Auxiliary Data Center located at DOE's Lawrence Livermore National Laboratory ~1000 km from the Seattle–based DMC. The ADC replicates all primary functions of the IRIS DMC and ensures that in the event the DMC in Seattle becomes inaccessible for any reason, the ADC can continue operating independently.
1.2.2 Connecting Big Data to HPC and "Cloud"			
NGEO Data Management System does not function well in the cloud or operations are prohibitively expensive	M	H	In that event, our plan is to operate primary dedicated infrastructure at IRIS and UNAVCO, but move to a shared ADC architecture in the cloud. We will still provide training and support for geoscientists unfamiliar with HPC and cloud computing environments.
1.3.1 Education, Workforce Development, and Public Outreach			
Loss of external REU funding	L	H	If renewal proposals to the NSF REU program are not successful, other EWO staffing and scope would be reduced to allow the internship program to continue.
NSF-mandated reduction in travel	M	H	Dissemination of resources and professional development of instructors and early career investigators would have to be modified to be almost exclusively virtual.
1.3.2 Workforce and Diversity Initiative			
Insufficient field equipment to meet demand	M	M	Funds are budgeted for additional equipment in later years of project.

Performance Assessment

Critical self-assessment of each NGEO facility and program will include establishing and monitoring key performance indicators (KPI) that reflect the performance of each facility or program. Comparison of performance against these metrics will be included in our quarterly report to the NSF as part of our assessment strategy. We expect to work with the NSF to develop KPIs for each of the foundational and frontier facilities and programs described in this proposal. In collaboration with UNAVCO, we will also maintain a comprehensive database of peer-reviewed publications that use NGEO data and will provide an annual report to the NSF with an analysis of NGEO-related publications.

We will conduct out-briefings of PIs for experiments supported by PASSCAL and the NSGF facilities to collect information on the quality of the service provided by IRIS and solicit suggestions for improvement. Regular facility reviews are another facet of our plan for critical self-assessment and will take two forms. First, facility performance will be routinely monitored and reviewed internally during meetings of the appropriate NGEO governance committees. In this way, IRIS will evaluate the performance of each facility annually, identifying any performance issues and taking immediate corrective action. Second, IRIS regularly organizes external reviews of its major facilities. These two- to three-day reviews, including site visits to the facility, are conducted by an independent panel of experts appointed by the IRIS Board of Directors. The NSF attends the reviews, and the review committee's report will be publicly available to the NSF and members of the geoscience community via the NGEO website. The most recent of these external reviews was of the Global Seismographic Network in July 2015. We plan to review both of the proposed new facilities—the Near-Surface Geophysics Facility and the PASSCAL MT facility—during the first five years of the NGEO.

The IRIS EWO portfolio will be evaluated somewhat differently through a strategic combination of internal and external evaluation practices applied throughout the life cycle of a project with the goal of maximizing the desired programmatic impact. This approach, based on the Collaborative Impact Analysis Method (Davis and Scalice, 2015), combines staff knowledge of programs and products, audiences, and content with the expertise of an outside evaluator. This combination captures the effects on the behaviors, attitudes, skills, interests, and/or knowledge of users and program participants, while achieving efficiencies by having IRIS staff conduct much of the development of assessment instruments, data collection efforts, and preliminary data analysis. To ensure success, an external evaluator provides consultation, review, feedback, and more robust data analysis. Risks are monitored on a project-by-project basis as part of the evaluation process, allowing resources to be reallocated as needed to keep projects on schedule.

Annually, each project in IRIS's EWO portfolio is reviewed jointly with the external evaluator, and together they score the project using a qualitative rubric based on best practices. The outcome of each consultation is the project score as well as steps to improve the project's impact, which drives the continuous improvement process (Taber et al., 2016). The adoption of this approach has resulted in a more robust software development cycle, with clear needs assessment, SMART (specific, measurable, attainable, relevant, time bound) objectives, and usability testing for all new software. Where simple counts had been used in the past, gaps in measuring the impact of other activities have been identified and filled with online and in-person surveys. Periodically, each project prepares a report on the impact of the evaluation on the project going forward. These reports are then used for high-level cross program analysis and strategic planning.

NGEO Management, Governance, and Community Engagement – WBS 1.4

IRIS and UNAVCO propose to partner in the operation and management of the NGEO as a facility "Center of Excellence" that blends the expertise of professional staff with community oversight to support and facilitate innovations in research and education in the geosciences. This partnership will enable closer integration and coordination between geodetic and seismological facilities and programs while providing new facility capabilities for other geophysical disciplines. The proposed partnership maintains the community strengths and depth of expertise that have driven innovation in instrumentation and the use of seismic and geodetic data over the past decades, while facilitating new cross-disciplinary discovery and uses of data and data products going forward.

IRIS and UNAVCO are submitting separate proposals to manage and operate the various components outlined in the NGEO solicitation. If both proposals are successful, IRIS and UNAVCO have agreed to jointly operate the NGEO within the framework of a common management and governance model. While this model has been developed assuming only two entities are operating NGEO facilities, the concept could be expanded to accommodate additional organizations that might be involved in operating NGEO facilities by expanding the membership of the management and governance committees.

NGEO Management Structure

IRIS and UNAVCO will utilize a corporate partnership model to manage the NGEO. This model for multicompany project management has been successfully used by major corporations such as General Motors, Proctor & Gamble, WalMart, and Boeing in a variety of situations (Baker, 2010). In this model, IRIS and UNAVCO will remain separate consortia and nonprofit corporations, with separate Boards of Directors, Presidents, and employees. **Figure MG-1** shows the NGEO management structure. A **Joint Executive Committee** consisting of the Presidents, Board Chairs, and Vice Chairs of both IRIS and UNAVCO will oversee a single, integrated NGEO management and governance structure. As a subcommittee of both Boards, the decisions and recommendations of the Joint Executive Committee will have to be endorsed by both the IRIS and UNAVCO Boards. The Joint Executive Committee will approve the Annual Plan and Budget (AP&B) submission to the NSF within the parameters of IRIS and UNAVCO's individual awards, oversee execution of the AP&B by IRIS and UNAVCO management, make decisions, recommend policy, and provide guidance on resource allocation at the NGEO level, and task advisory committees and working groups, as needed. IRIS and UNAVCO managers and staff, led by the senior executive leadership of each corporation, will be responsible for execution of the AP&B.

A **Joint Management Team** consisting of the IRIS and UNAVCO Directors responsible for the major NGEO foundational activities—Geophysical Networks and Portable Instrumentation; Geophysical Data Services and Products; and Education, Workforce, and Outreach—will have day-to-day responsibility for execution of the NGEO AP&B and for coordinating activities between IRIS and UNAVCO. The six members of the Joint Management Team will meet monthly via telecon and serve as ex officio members of the Joint Executive Committee to ensure direct communication between the executive and operational management of the NGEO. IRIS and UNAVCO managers and staff, led by the senior executive leadership of each corporation, will be responsible for execution of the AP&B.

NGEO MANAGEMENT STRUCTURE

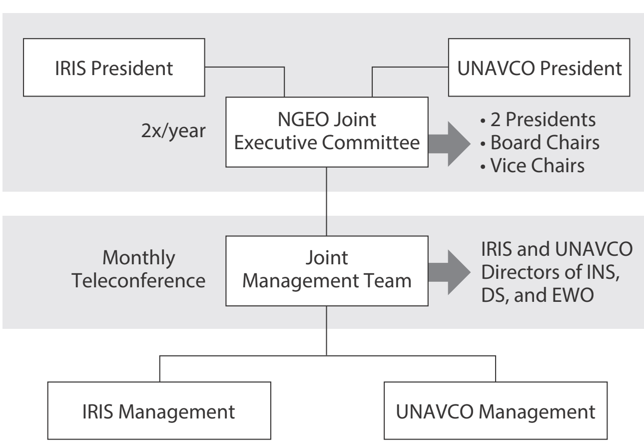


FIGURE MG-1. NGEO management structure. See text for explanation.

Before adopting this management model for the NGEO, we considered several alternative models, including a full corporate and organizational merger of IRIS and UNAVCO and their consortia, or the creation of an independent NGEO Office that would oversee an integrated advisory and governance structure, and execution of the AP&B, as was initially done for EarthScope. We did not pursue the NGEO Office model because the office would lack the personnel or authority to make or implement budget or operational decisions and would add an additional layer of management that would increase NGEO administrative costs. The IRIS and UNAVCO Boards discussed, but did not pursue, a corporate merger at this time as the anticipated cost savings were small relative to the loss of discipline-specific expertise and the agility each organization has now to respond to community needs that has driven many of the key scientific advances in recent years. The IRIS and UNAVCO consortia serve large, but still relatively distinct, communities (e.g., there is very little overlap in attendance (<5%) at the UNAVCO and IRIS biennial workshops), and there is a strong consensus on both Boards that these communities continue to benefit from the existence of separate organizations. In addition, each organization manages and operates facilities outside of the NGEO solicitation. The NGEO presents an opportunity to foster enhanced collaboration between these communities, and by building on the unique strengths of IRIS and UNAVCO and the communities they support, we believe a corporate partnership model will be the best approach for management of the NGEO facility.

Community Governance Structure – WBS 1.4.1

One of the greatest strengths of the facilities and programs managed by IRIS and UNAVCO has been the strong engagement of the broader scientific community in their governance and operation. The feedback and advice from a community of active scientists has been essential to the success and development of the programs and facilities, and has ensured that they continue to serve the highest priority needs of the scientific community. We are committed to operating the NGEO transparently, responsively, and cost effectively to address scientific priorities through community governance and oversight.

Community oversight of the NGEO facilities will be provided by three advisory committees (ACs) (**Figure MG-2**). The ACs will be responsible for gathering community input on the operation of the NGEO facilities, including budgetary prioritization and planning, as well as providing recommendations on future facility needs.

- **Instrumentation and Network Services Advisory Committee:** Responsible for providing community input on the wide range of continuously operating global and regional geophysical networks and portable instrumentation operated by the NGEO.
- **Data Services and Products Advisory Committee:** Responsible for providing community input on the collection, quality assurance, curation, management, and distribution of the NGEO geophysical data and data products.
- **Education, Workforce, and Outreach Advisory Committee:** Responsible for providing community input on the range of the NGEO programs designed to disseminate Earth science results to a wide range of audiences, enhance geoscience education, support development of the geoscience workforce, and enhance participation of underrepresented groups in the geosciences.

Membership of the ACs, which will include representatives from the geodesy and seismology communities, and other geophysical disciplines, will be appointed by the IRIS and UNAVCO Boards. Membership will be drawn from academic institutions, government agencies, and industry in the United States or abroad. AC members will typically serve a term of three years. We expect the ACs will hold two face-to-face meetings each year.

Due to the complexity and diversity of instrumentation networks, and associated infrastructure and services within the NGEO, we will establish three standing committees under the Instrumentation and Network Services Advisory Committee: **Global and Regional Seismic Networks**, **Portable Geophysical Instrumentation**, and **Polar Networks and Instrumentation**. These three standing committees will provide community input on the planning and operation of specific instrumentation facilities to the Instrumentation and Network Services Advisory Committee. We expect these standing committees to hold two face-to-face meetings a year, except the Polar Networks and Instrumentation committee, which will have one annual face-to-face meeting. In accordance with the MOU between the NSF and the USGS, IRIS will retain a separate **GSN Standing Committee** as a focused technical group to provide advice on the GSN to IRIS and USGS management. The Chair of the GSN Standing Committee will serve ex officio on the NGEO Global and Regional Networks Standing Committee.

Additional working groups will be appointed, as needed, to provide community input on the planning and operation of specific NGEO facilities, or to address issues identified by the ACs. We expect these working groups to have specific, time-limited charges and appropriate reporting lines, and to meet virtually.

Good communication between these governance committees and the IRIS and UNAVCO Boards will be very important for the success of this governance model. Each AC and SC will have a liaison from the IRIS and UNAVCO Boards that will attend their meetings and ensure the Boards are aware of community input regarding these facilities. A **Joint Advisory Committee** will coordinate communication among the various NGEO advisory and standing committees, and between these committees and the Joint Executive Committee. The Joint Advisory Committee will be composed of the chairs of the ACs and SCs and will be co-chaired by the vice chairs of the IRIS and UNAVCO Boards. The Joint Advisory Committee will coordinate planning across the facility, review and discuss recommendations and reports from the ACs and SCs, collate questions from ACs and SCs that require higher level response, and identify cross-NGEO opportunities to enhance operations or improve the scientific effectiveness of the NGEO facilities. We anticipate the Joint Advisory Committee will meet twice a year.

Overall, this integrated governance structure is significantly streamlined from what IRIS and UNAVCO maintained for

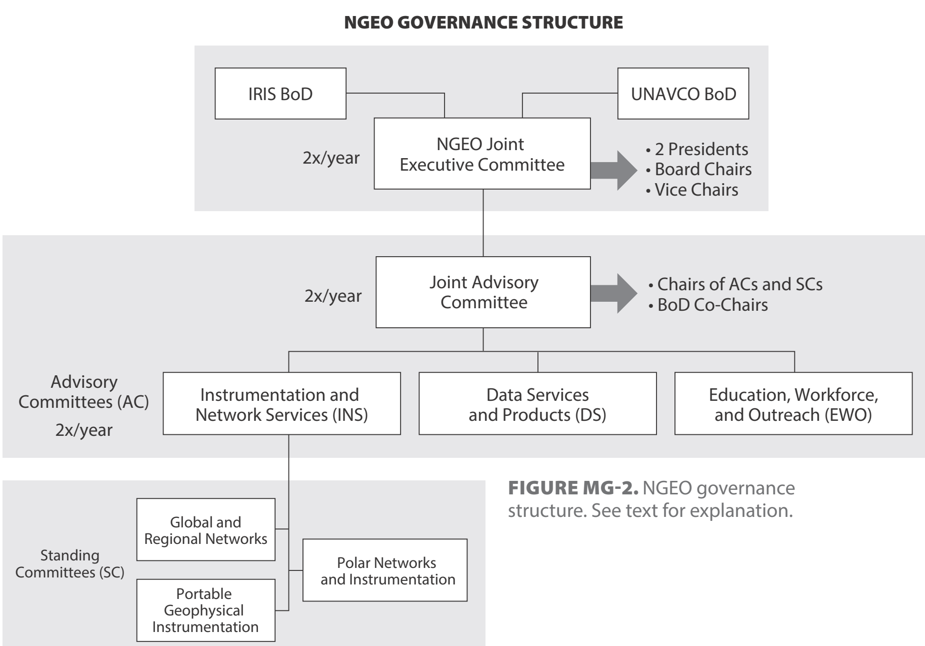


FIGURE MG-2. NGEO governance structure. See text for explanation.

SAGE (Seismological Facilities for the Advancement of Geoscience and EarthScope) and GAGE (Geodesy Advancing Geosciences and EarthScope), respectively, with the total number of committees reduced from 15 standing and advisory committees in SAGE and GAGE to just eight committees for the NGEO.

Community Activities – WBS 1.4.2

Continual engagement of the diverse community that the NGEO facilities will support is essential to the facility's long-term success and was identified in the "Futures" Facility Workshop Report as one of the fundamental characteristics of a "Facility Center of Excellence" (Aster and Simons, eds., 2015). Participation in the NGEO governance committees, online webinars, community workshops, and facility and scientific planning activities will engage and support a diverse range of geoscience professionals and facility specialists, engage the next-generation of geoscientists, and cultivate leadership skills within the NSF-supported academic research community. As we broaden the community of Earth scientists who use the NGEO facilities, this engagement will be particularly important in order to provide new users with information about facility capabilities, training in how to use these facilities, and forums for input and feedback on facility needs and operations.

NGEO Website. IRIS and UNAVCO will establish an NGEO website as the public face of the facility and provide a single site through which both the geoscience research community and the general public can obtain information about the NGEO facilities and the science these facilities support. For the research community, the NGEO website will provide access to information about facility management, organization, and governance; facility capabilities and how to use the facilities; and the geodetic, seismic, and other geophysical data and data products available through the NGEO. The NGEO website will also provide information on upcoming meetings and workshops, available resources such as teaching and learning tools, support for early career investigators, short courses, publications, and news items related to the NGEO facility. These Web pages will also include timely information about recent geophysical events, publications, and other resources of particular interest to the research community and the broader general pubic.

Social Media and Online Webinars. Increasingly, social media and online activities are being used to engage researchers and broader audiences. IRIS and UNAVCO plan to significantly expand the social media presence of the NGEO. The NGEO will host regular Web-based seminars featuring contributions from our staff, members of the geoscience community supported by NGEO facilities, and other professionals across the geosciences. These webinars will highlight recent scientific results based on observations and data obtained from the NGEO facilities. Other webinars will be directed primarily toward early career investigators and focus on professional or technical development of members of the geosciences community. These webinars will be modeled after the current IRIS webinar series that draws up to 100 real-time participants and for which there have been over 6000 views of the nearly 100 webinars that are available online and on the IRIS YouTube channel.

E-Newsletter and Other Publications. For more in-depth coverage, IRIS and UNAVCO plan to publish a quarterly NGEO e-newsletter with information for users of the NGEO facilities and the broader geosciences community. The newsletter will highlight facility-supported research results and field experiments, provide summaries of recent facility-related workshops and meetings, announce new data products and educational resources available to geoscientists, and provide information on upcoming workshops, meetings, and webinars. While most interactions with the community will be via electronic formats, we will also continue to create print materials as needed to reach new audiences at meetings and other venues (e.g., fliers describing the NGEO facilities, planning summaries, or workshop reports).

Community Workshops. Community workshops are essential to bring together geoscience researchers to discuss recent scientific advances, learn about new technologies and facility capabilities, plan new initiatives, and stimulate interactions among individuals and between research groups. As a facility operator, workshops are also a very effective way to get community input on the operation of the facilities and learn about needs and priorities for future facility capabilities. As we broaden the geoscience community the NGEO supports, these workshops will help integrate new communities with the more traditional seismic and geodetic communities. Workshops are also extremely valuable to early career investigators (graduate students, postdocs, and pre-tenure facility), helping them showcase their work, network with peers, establish professional connections with more established researchers, and forge new collaborations. At the most recent biennial IRIS workshop in June 2016, nearly one-third of the 235 participants were early career investigators, and 94% of those early career participants who responded to a post-workshop survey agreed that the workshop was a valuable use of their time.

The types of NGEO workshops we hold will depend on the needs of the research community. We envision a mix of smaller, topical workshops with a particular scientific or technical theme (e.g., cross-coastal science and facility needs or applications of near-surface geophysics) that will change annually, and larger, less frequent (e.g., every second year) workshops that bring together a broad cross section of the research community that uses the NGEO facilities. This will allow us to both foster cross-disciplinary interactions and nurture new communities within the NGEO, as well as regularly bring the broader seismology and geodesy communities together. The selection of workshop themes and formats will be made by the NGEO Joint Executive Committee based on recommendations of the NGEO governance committees. Both IRIS and UNAVCO will provide funding and organizational and logistical support for the workshops, but the workshops themselves will be planned by workshop organizing committees composed of community members.

IRIS Management Structure and Business System Capabilities

IRIS Corporate Management Structure – WBS 1.4.3

A nine-member Board of Directors serves as the major decision-making body for IRIS, guiding the programmatic, management, and fiscal activities of the Corporation. It sets goals and policies, reviews and approves program plans and budgets, and directs the activities of the President. The IRIS bylaws give the Board authority to establish committees to provide advice on facilities and programs managed by the Corporation. The Board of Directors is elected by the members of the IRIS Consortium and serve three-year terms. Membership on the Board of Directors is restricted to individuals from Consortium member institutions, but advisory committees, and other committees and working groups, can have members from any organization (academic institution, government agency, or industry).

IRIS's central and administrative functions will continue to be carried out through a Headquarters Office in Washington, DC. Overall management will remain under the direction of a full-time President, Robert Detrick, appointed by the Board, who works with a Senior Management Team that includes the directors 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 (**Figure IM-1**). The various facility capabilities will be implemented by a combination of IRIS employees, subawards, or partnerships that varies depending on the requirements of individual programs.

In the NGEO, the Instrumentation Services Directorate will be headed by Robert Woodward, who will be responsible for the GSN, PASSCAL, PASSCAL Polar Support Facility, PASSCAL Magnetotelluric Facility, and Near-Surface Geophysics Facility (**Figure IM-1**). Each of these facilities has a manager who reports to the Instrumentation Services Director (some managers are responsible for more than one facility). The Data Services Directorate will be led by Timothy Ahern, who will be responsible for management of the IRIS Data Management Center and all data-related services, quality control, and products. John Taber will lead the Education and Public Outreach Directorate, and will be responsible for all IRIS education, public outreach, and workforce development activities. IRIS Financial Services will be led by Chief Financial Officer Candy Shin, who will be responsible for accounting, financial controls, payroll, insurance, inventory, and COTS purchasing. The Director of Program Support and Special Projects will be led by Rob Woolley, who will be responsible for sponsored projects (award compliance, non-COTS contracts, procurement, proposal submissions), management policies and procedures, publications, information technology, and human resources.

IRIS currently has 64 full-time staff located primarily at IRIS Headquarters in Washington, DC, at the IRIS Data Management Center in Seattle, Washington, and at field offices in Socorro,

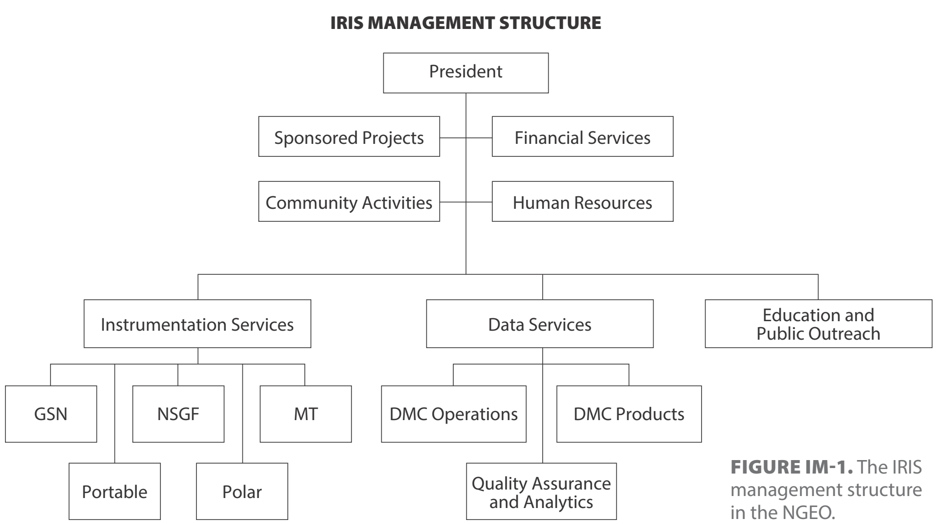


FIGURE IM-1. The IRIS management structure in the NGEO.

New Mexico, and Anchorage, Alaska. Approximately 75 full-time equivalents are supported through major IRIS subawards to the New Mexico Institute of Mining and Technology, the University of California, San Diego, and the University of Wyoming. The USGS facility in Albuquerque, New Mexico, provides significant dedicated support for the GSN, but is separately funded by the USGS.

Workforce Management and Technical Planning

IRIS's success depends on a geographically and intellectually diverse workforce. IRIS employees include PhD scientists, office managers, accountants, information technology experts, educators, administrative and clerical practitioners, and engineers spread across seven states and four time zones. Keeping this impressive talent pool productive, engaged, compensated, and improving is workforce management. To make sure that IRIS has the latest in workforce management practices and technologies, we rely on ADP TotalSource, a Professional Employer Organization. ADP TotalSource is a comprehensive global provider of cloud-based Human Capital Management (HCM) solutions that provides IRIS with services for human resources, payroll, time card management, and tax and benefits administration. ADP is a leader in business outsourcing services, analytics and compliance expertise. Established in 1949, ADP is one of the oldest and largest HCM providers in the world. With ADP TotalSource, IRIS has the best in workforce management tools that are available anywhere.

The process for planning future operations and technical initiatives is embedded in the annual budget preparation and review process. The process begins with IRIS and UNAVCO seeking guidance from the NSF regarding the next year's budget in January. Using the NSF's guidance, the Boards will issue specific guidance, coordinated through the Joint Executive Committee, to their respective management teams and the NGEO governance committees. This guidance will provide strategic direction as well as budget targets for each program area. Governance committees representing the various NGEO stakeholder communities will meet and discuss operational plans and technical priorities constrained by the budget guidance for the next year. The resulting plans and priorities are shared among governance committee chairpersons and brought into alignment by a Joint Management Team. The Joint Management Team recommends the annual plan and budget to the NGEO Joint Executive Committee and the IRIS and UNAVCO Boards for approval (see **Figure MG-2**). The Board-approved plans and budgets will be submitted separately by IRIS and UNAVCO to the NSF for their approval and funding. Using this process, we will involve a broad cross section of NGEO stakeholders in the planning for future operations and initiatives.

> *The Incorporated Research Institutions for Seismology (IRIS) is an extremely well-managed and effective organization that has, through its commitments to the collection and open dissemination of the highest quality seismological data, transformed the discipline of seismology. All mail reviews received as part of this review recognized and praised the quality and effectiveness of IRIS management and leadership.*
>
> – 2009 IRIS Management Review (page 2)

Business System Capabilities

A Financial Services group, with a staff of six employees, is responsible for the accounting and financial operations of IRIS, using the accounting software Deltek GCS Premier®, which is designed for government contractors to manage projects in compliance with government regulations. Each award is set up with an account code that tracks all expenses and revenues for that award. Multiple budgets (subtasks) may be set up under each award code and rolled up to the award level.

Equipment records are maintained in the accounting system and identified by funding source for award reporting purposes. The largest inventory tracking system for the facility is implemented by the PASSCAL Instrument Center, using a barcoding system for physical inventory control and management.

Procurement activities are overseen by both the Financial Services group, which handles routine, COTS procurements, and the Sponsored Projects Office, which oversees and advises program staff on non-COTS procurements, including requests for proposals and independent contractor agreements.

Financial and Audit Controls

As required for Federal awards, IRIS has a Single Audit conducted annually in accordance with 2 CFR §200.514. In 2015, IRIS accepted proposals from qualified CPA firms and engaged Aronson LLC to conduct the Single Audit for IRIS fiscal years 2015–2017. A Budget and Finance Subcommittee has been charged with assisting and providing recommendations to the IRIS Board of Directors on its financial management responsibilities, which include accepting and reviewing reports provided by external auditors.

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Glossary of Acronyms

AASG .... Association of American State Geologists
AC...................... Advisory Committee
ADC .... Auxiliary Data Center
AGU .... American Geophysical Union
AP&B .... Annual Plan and Budget
ARRA................ American Recovery and Reinvestment Act
ASL.................... Albuquerque Seismological Laboratory – USGS facility
ASTC................. Association of Science – Technology Centers
CIG .... Computational Infrastructure for Geodynamics – NSF-funded program
COTS................. Commercial off the shelf
CTBTO .... Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization
CZO................... Critical Zone Observatories - an NSF-funded program
DAS .... Data Acquisition System
DCC................... Data Collection Center
DMC.................. Data Management Center
DMS................... Data Management System
DOD .... Department of Defense
DOE................... Department of Energy
DOI.................... Digital Object Identifier
DS .... Data Services, an IRIS directorate
EAR .... NSF's Division of Earth Sciences
EarthCube......... An NSF Geosciences Cyberinfrastructure program
EGU................... European Geosciences Union
EMIW................ Electromagnetic Induction of the Earth Workshop
EPO.................... Education and Public Outreach
EWO.................. Education, Workforce Development, and Public Outreach
EPSCoR............. Experimental Program to Stimulate Competitive Research - an NSF program
FDSN................. International Federation of Digital Seismograph Networks
FTE .... Full-time equivalent
G&A .... A general and administrative expense
GAGE................ Geodesy Advancing Geoscience and EarthScope (UNAVCO's current award from NSF)
GABBA .... Global Array of Broadband Arrays – as described in this proposal
GeoSciCloud .... An NSF-funded EarthCube project

GeoWS .... An NSF-funded EarthCube project
GLISN .... Greenland Ice Sheet Monitoring Network – MRI funded
GPS .... Global Positioning System
GNSS .... Global Navigation Satellite System
GNSS-IR .... GNSS-Interferometric Reflectometry
GNSS-Met .... GNSS-Interferometric Meteorology
GPS-IR .... GPS-Interferometric Reflectometry
GRACE .... Gravity Recovery and Climate Experiment – NASA satellite program
GSA .... Geological Society of America
GSN .... Global Seismographic Network
HDF5 .... A data model, library, and file format for storing and managing geophysical data
HPC .... High Performance Computing
IASPEI .... International Association of Seismology and Physics of the Earth's Interior
IDA .... International Deployment of Accelerometers – UCSD operated component of the GSN
InSAR .... Interferometric Synthetic Aperture Radar
InTeGrate .... NSF-funded undergraduate geoscience curriculum development project led by Carleton College
IPCC .... Intergovernmental Panel on Climate Change
IRIS .... Incorporated Research Institutions for Seismology
IUGG .... International Union of Geodesy and Geophysics
KPI .... Key Performance Indicators
LDEO .... Lamont-Doherty Earth Observatory of Columbia University
LIDAR .... Light Detection and Ranging – a surveying method that measures distance using laser light
LLNL .... Lawrence Livermore National Laboratory – site of IRIS ADC
MOU .... Memorandum of Understanding
MRI .... Major Research Instrumentation – program at NSF
MT .... Magnetotelluric
MUSTANG .... Modular Utility for STAtistical kNowledge Gathering
NASA .... National Aeronautics and Space Administration
NDAP .... NGEO Data Access Point
NIMS .... Narod Intelligent Magnetotelluric System
NGEO .... National Geophysical Observatory for Geoscience
NGSS .... Next Generation Science Standards
NMT .... New Mexico Institute of Mining and Technology
NSGF .... Near-Surface Geophysical Facility
NOAA .... National Oceanic and Atmospheric Administration
NRC .... National Research Council

NSF .... National Science Foundation

NSTA .... National Science Teachers Association

OBSIP .... Ocean Bottom Seismograph Instrument Pool – supported by NSF Division of Ocean Sciences

OCE .... NSF's Division of Ocean Sciences

OSU .... Oregon State University

PASSCAL .... Portable Array Seismic Studies of the Continental Lithosphere

PBO .... Plate Boundary Observatory – UNAVCO-operated geodetic component of EarthScope

PCAST .... President's Council of Advisors on Science and Technology

PI .... Principal Investigator

PIC .... PASSCAL Instrument Center – at New Mexico Tech

PFO .... Pinyon Flat Observatory – operated by UCSD

PLR .... NSF's Division of Polar Programs

QCN .... Quake Catcher Network

RAMP .... Rapid Array Mobilization Program – IRIS program to provide instruments for event response

RESESS .... Research Experiences in Solid Earth Sciences for Students – a UNAVCO diversity program

REU .... Research Experiences for Undergraduates - an NSF program

SACNAS .... Society for Advancement of Chicanos/Hispanics and Native Americans in Science

SAGE .... Seismological Facilities for the Advancement of Geoscience and EarthScope (IRIS' current award from NSF)

SC .... Standing Committee

SEED .... Standard for the Exchange of Earthquake Data

SEG .... Society of Exploration Geophysics

SERC .... Science Education Resource Center – a program at Carleton College

SSA .... Seismological Society of America

STANYS .... Science Teachers Association of New York State

STEM .... Science, Technology, Engineering, and Mathematics

SZO .... Subduction Zone Observatory

TA .... USArray Transportable Array

UCSD .... University of California, San Diego

USGS .... U.S. Geological Survey

UTEP .... University of Texas, El Paso

UWyo .... University of Wyoming

VBB .... Very Broad Band

WBS .... Work Breakdown Structure

WDS .... World Data System

XSEDE .... Extreme Science and Engineering Discovery Environment – an NSF-funded facility