VOLUME I | APPENDIX: PROGRAM DESCRIPTIONS

CONTENTS

1 | GLOBAL SEISMOGRAPHIC NETWORK

HISTORICAL CONTEXT OF CURRENT OPERATIONS

The Global Seismographic Network (GSN) is a state-of-the-art, digital network of scientific instrumentation and inheritor of a century-long tradition in seismology of global cooperation in the study of Earth. The network was built and is operated cooperatively by IRIS and the U.S. Geological Survey, with coordination and contributions from other U.S. government agencies and with the international community. The network has multiple scientific uses in several disciplines of Earth science that serves societal needs for Earth observations, monitoring, research, and education. The instrumentation is capable of measuring and recording with high fidelity all seismic vibrations, from high-frequency, strong ground motions near an earthquake to the slowest fundamental oscillations of Earth excited by the largest great earthquakes.

The GSN concept is founded upon global, uniform, unbiased Earth coverage by a permanent network of over 130 stations (and Affiliates) with real-time data access. The instrumentation is modular, enabling it to evolve with technology and science needs. Equipment standardization and data formats create efficiencies for use and maintenance. Telecommunications are heterogeneous, using both public and private Internet links as well as dedicated satellite circuits. All of the data are distributed without restriction as soon as technically feasible, nearly all of it in real time.

The network is both benefactor and beneficiary of a government-university cooperation involving the NSF, the USGS, the Department of Defense, NASA, and NOAA. GSN is a foundation for both the USGS Advanced National Seismic System (ANSS) and the USArray Reference Network, and provides the critical core data for the U.S. Tsunami Warning Centers and other international tsunami warning systems, and for the international Greenland Ice Sheet Monitoring Network (GLISN). The International Monitoring System for the Comprehensive Nuclear Test Ban Treaty uses data from GSN stations. GSN is an official U.S. observing system component of the Global Earth Observation System of Systems (GEOSS). With IRIS a founding member of the International Federation of Digital Broadband Seismographic Networks (FDSN), GSN serves as key component of the FDSN backbone. GSN serves as a fiducial reference network for PASSCAL experiments and other international portable deployments throughout the world. Primarily operated and maintained through the USGS Albuquerque Seismological Laboratory (ASL) and the University of California at San Diego (USCD), GSN is joined by independent national and international Affiliate stations and arrays. Affiliate stations provide all of the necessary equipment to meet GSN design goals, fund their own operations and maintenance following GSN standards, and distribute their data as a part of GSN. Many GSN stations have been enhanced through international cooperative efforts, including the contribution of seismic equipment, telemetry, and other support in kind. International partners include network operators in Australia, Botswana, Canada, China, France, Germany, Great Britain, Italy, Japan, Kazakhstan, Kyrgyzstan, Korea, Mexico, New Zealand, Norway, Peru, Russia, Singapore, Spain, United Arab Emirates, and others.

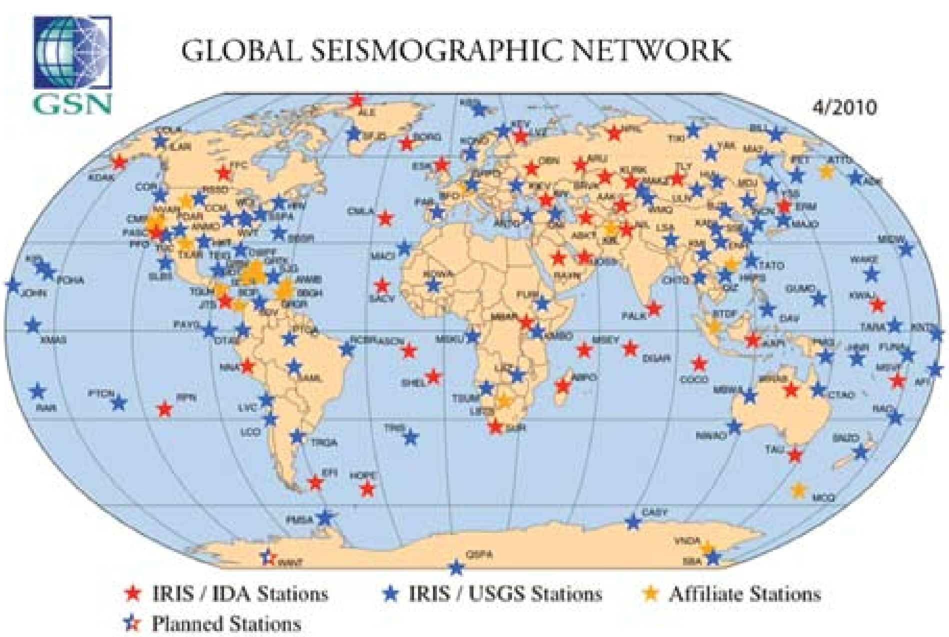


Figure A1.1. Status of the GSN in 2010 showing stations operated by the USGS Albuquerque Seismological Laboratory, the IDA group at the University of California, San Diego, and GSN Affiliates.

GSN is an educational tool for the study of Earth. With the ease of data access and blossoming computer technology, the data are now routinely used in introductory college courses, and high school use is rising. The stations themselves are focal points for international training in seismology. Real-time access to the data has led to rapid analysis of earthquake locations and their mechanisms, bringing public awareness of earthquakes as scientific events, not just news events.

International, global seismographic coverage was born at the beginning of the twentieth century when a network of more than 30 Milne seismographs first spanned the globe—in essence the first global seismographic network. In 1960, the analog World Wide Standard Seismograph Network (WWSSN) of 100+ seismic stations was initiated to provide basic global coverage for seismological research and monitoring nuclear tests. Data from this network formed the core for modem seismology and discoveries leading to plate tectonics. Entering the digital age in the 1970s, the USGS/Advanced Research Projects Agency (ARPA) Seismic Research Observatories (SRO) of both underground and borehole seismometers and the NSF-sponsored UCSD International Deployment of Accelerometers (IDA) initiated a new era of large-scale, digital seismological studies.

In the 1980s, seismometers with feedback electronics became available with very broad bandwidth, high dynamic range, and linearity for recording the largest earthquake signals, and instrumental noise below the lowest natural seismic background noise. Digitizers were developed with more than 140 dB dynamic range to encode the analog signals from these new broadband sensors. Computer costs declined while processing speeds and recording capacities increased exponentially.

This strong technological foundation came at a time when the science of seismology had advanced theoretically beyond its observational capacity. The questions being posed by the science could not be answered with the limited data available. At the same time, the view of Earth as a system was coming into focus. Seismology, with its unique ability to "see" into the planet, was called to image Earth's interior and provide

GSN RELATIONSHIPS AND PARTNERSHIPS

GSN MANAGEMENT HAS DIRECT RELATIONSHIPS WITH:

- Geophysical Survey of the Russian Academy of Sciences
- Chinese Earthquake Administration
- Geoscience Australia
- Geological Survey of Canada
- University of Brazil
- Germany's GeoForschungsZentrum, Bundesanstalt fur Geowissenschaften und Rohstaffe (Geological Survey), and Alfred Wegner Institute for Polar Research
- Italy's Istituto Nazionale di Geofisica e Vulcanologia (INGV)
- Mexican National Seismic Network
- British Geological and Antarctic Surveys
- Japan's National Research Institute for Earth Science and Disaster Prevention (NIED), University of Tokyo Earthquake Research Institute, Japan Marine Science and Technology Center (JAMSTEC), and Japan Meteorological Agency
- France's Institut de Physique du Globe de Paris and Laboratoire de Détection Géophysique (LDG)
- New Zealand Geological and Nuclear Sciences
- Spain's Instituto Geographico Nacional (IGN)
- Chile's Fundacion Andes
- Singapore's Meteorological Service
- Hong Kong Observatory
- Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) International Monitoring System (IMS) and Global Communications Infrastructure (GCI)
- International Ocean Network (ION)
- Greenland Ice Sheet Monitoring Network (GLISN)
- International Federation of Broadband Digital Seismic Networks (FDSN)
- Global Earth Observation System of Systems (GEOSS)

NATIONAL PARTNERSHIPS INCLUDE:

- National Science Foundation (Earth, Oceans, Atmospheres and Polar Programs)
- USGS (Albuquerque, Reston, Golden and Menlo Park)
- National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS)
- Pacific Tsunami Warning Center (PTWC) and West Coast and Alaska Tsunami Warning Center (WC/ATWC)
- National Aeronautics and Space Administration (NASA)/Jet Propulsion Laboratory (JPL)
- Air Force Technical Applications Center (AFTAC)
- U.S. State Department Verification Monitoring Task Force
- UNAVCO Inc.
- University of California at San Diego (UCSD)
- Harvard University
- Caltech/University of Southern California
- Saint Louis University
- Oregon State University
- University of Arizona
- University of California at Berkeley
- Penn State University
- University of Texas at Austin
- Carnegie Institution of Washington
- University of Hawaii at Manoa

GSN AND MONITORING: EARTHQUAKES, TSUNAMI WARNING, NUCLEAR TREATY VERIFICATION

GSN is a real-time network whose data are routinely used by operational monitoring groups, both in the United States and internationally. In the United States, 19 GSN stations are included in the USGS Advanced National Seismic System. The National Earthquake Information Center receives data from all real-time GSN stations globally for earthquake locations. GSN data are essential input to the USGS PAGER (Prompt Assessment of Global Earthquakes for Response) automated alarm system used to rapidly and accurately assess the severity of damage caused by an earthquake and to provide emergency relief organizations, government agencies, and the media with an estimate of the societal impact from the potential catastrophe. PAGER rapid assessments of the disastrous, 2008 Wenchuan, China, 2010 Port-au-Prince, Haiti, and 2010 Maule, Chile, earthquakes were used by the United States Office for Disaster Assistance, United Nations, World Bank, and others. Thirty-three GSN stations (and seven Affiliates) now participate in the Comprehensive Test Ban Treaty International Monitoring system, and nearly 50 will participate when communications arrangements are completed. GSN is used by the Air Force Technical Applications Center to augment research data from its U.S. Atomic Energy Detection System. The Pacific Tsunami Warning Center and West Coast/Alaska Warning Center each use data from over 100 real-time GSN stations, which were fundamental to the tsunami warning for the Mw 8.8 Concepcion, Chile, earthquake of 2010. The Japan Meteorological Agency, Geosciences Australia, and GeoForschungsZentrum (Germany) each augment their own stations with over 100 GSN stations for tsunami warnings. The 12 GSN stations in Russia and the 10 in China form a core for their respective national seismic networks. Canada, Australia, and Kazakhstan link to real-time GSN stations in their respective countries to augment their national networks. GSN is an official contribution of the United States to the Global Earth Observation System of Systems.

fundamental physical data for other branches of the geosciences. Further, the deaths of several hundred thousand people in a single earthquake in Tang Shan, China, in 1976 and the billions of dollars lost worldwide in earthquake damage accentuated the need to understand better the dynamics of earthquakes in order to mitigate their hazards.

Meeting these opportunities and challenges, the IRIS Consortium initiated the GSN in 1986 with funding from the National Science Foundation, and in cooperation with the USGS. GSN built upon the foundation infrastructure of WWSSN, SRO, and IDA stations, which it extended to create new and more uniform coverage of Earth. The USGS ASL and UCSD IRIS/IDA were established as the prime network operators. Collaborations with IRIS member universities helped to establish higher density of GSN coverage within the United States. Growing slowly at first, then accelerating with funding from the nuclear verification community in anticipation of the Comprehensive Nuclear Test Ban Treaty, GSN is now the state-of-the-art digital network with terabytes of multi-use data from its 154 stations worldwide.

GSN's design goal is to record with full fidelity all seismic signals above Earth's background noise. GSN system bandwidth meets the diverse requirements of the scientific community, national/regional/local earthquake monitoring, tsunami warning networks, the strong-ground-motion engineering community, and nuclear verification programs. GSN sites have been selected to achieve the best possible quiet noise conditions, while balancing cost and logistics. With few exceptions, all GSN data are telemetered in real time to mission agencies and the IRIS Data Management Center. Established for seismology, the GSN infrastructure now hosts the world's largest microbarograph infrasound network, one of the major global GPS networks, as well as geomagnetic and weather sensors.

OPERATIONS & MAINTENANCE

The operations and maintenance of GSN are fundamentals, as GSN has shifted from deployment/installation to long-term sustainability of the network. Basic O&M responsibilities for the IRIS/IDA part of GSN are funded by IRIS/NSF, and for the IRIS/USGS part of the network by ASL/USGS, with substantial coordination and collaboration between the groups. GSN underwent a significant cost analysis of the operation and maintenance of the entire network in 2008. This analysis focused on GSN sustainability, and reviewed personnel, equipment, telemetry, international support, and other areas in the context of current and recent budgets.

Staffing costs are the largest single line item in GSN network budgets, with overhead costs second. IDA personnel are UCSD employees; ASL personnel include both USGS government employees and contractors (currently, Honeywell Technology Services Inc. [HTSI]). The HTSI contract provides for personnel, travel, and other services for USGS, and has its own program manager. ASL and IDA management work closely with each other and with IRIS management (together, forming the GSN Operations Group—chaired by the GSN Operations Manager), and interact directly and indirectly with the IRIS scientific community.

Both network operators fulfill the same basic functions in operating and maintaining GSN, and interact with each other through the Operations Group to share technology and techniques and develop procedures for standardized operations. Field, facility, and software personnel must manage the stations, not only the equipment (sensors, data acquisition, power, and telemetry), but also the data flow and metadata to ensure well-calibrated systems. Equipment must be procured, received, tested, integrated, inventoried, warehoused, shipped, and repaired. Station information, maintenance and installation reports, records of system modifications, export licenses, and shipping documents, supplies, and equipment schematics must be organized and maintained. Software and source codes must be maintained and tested across a variety of station configurations and throughout the data collection system, from the station data acquisition system, to the telemetry interface, to data archiving and delivery, to the IRIS DMS. Station state-of-health, telemetry systems, and data quality control must be monitored routinely. Close collaboration between GSN and DCC personnel is essential to diagnose and resolve data-quality problems. In addition to equipment and data issues, key to quality station operations is the establishment and maintenance of a rapport with the local hosts.

The staffing levels at IDA and ASL are ~11.4 and 22.8 FTEs, respectively, for about one-third and two-thirds of the GSN, respectively. These personnel levels supported field operations with station up time at about 85%—at historic highs—with high data quality overall. Enhancement of station performance beyond these levels requires additional personnel and increases in personnel productivity. The acceleration of GSN upgrades initiated in 2009 included supplemental personnel at IDA and ASL, as well as augmented travel support. By reducing the burden for maintaining obsolete equipment, the productivity of our GSN field staff with the new, standard equipment will allow for a shift in emphasis toward improved data quality and productivity for the whole network. This personnel-efficiency gain further underscores the fundamental importance for completing next-generation system (NGS) rollout expeditiously.

The O&M review included a systematic review of over 6,000 sensor-years of GSN seismometer failure and replacements rates. This study has yielded long-term expectation values for sensor replacements rates necessary to sustain GSN, and represents a quantitative improvement over prior "rules of thumb" for equipment amortization. Based upon actual GSN numbers, the yearly rates of seismometer procurements necessary for maintaining the network have been measured, and now serve as the sustainability metric for GSN. These measures have already affected GSN practice, with the network moving away from sensors with low mean-time-between-replacement (MTBR) to better-performing sensors. In particular, GSN has stopped purchasing prior-generation borehole sensors (relying on repairs instead), is supplementing borehole sites with higher-reliability broadband surface sensors, and is actively pursuing the establishment of specifications for the next-generation borehole sensors with better performance. Similarly, GSN is replacing problematic vault sensors having demonstrably low MTBR with better units.

The manufacturing lifetime of a data-acquisition system (DAS) is about 10 years, after which the manufacturer discontinues the product line (the original components become impossible to obtain) and no longer supports repairs. This progression has been observed in the past in GSN and was quoted by the vendor as the expected manufacturing life span of the NGS DAS. In the subsequent transition period, GSN must maintain and repair units internally, and may resort to

HISTORICAL REPLACEMENT RATES FOR GSN SEISMOMETERS

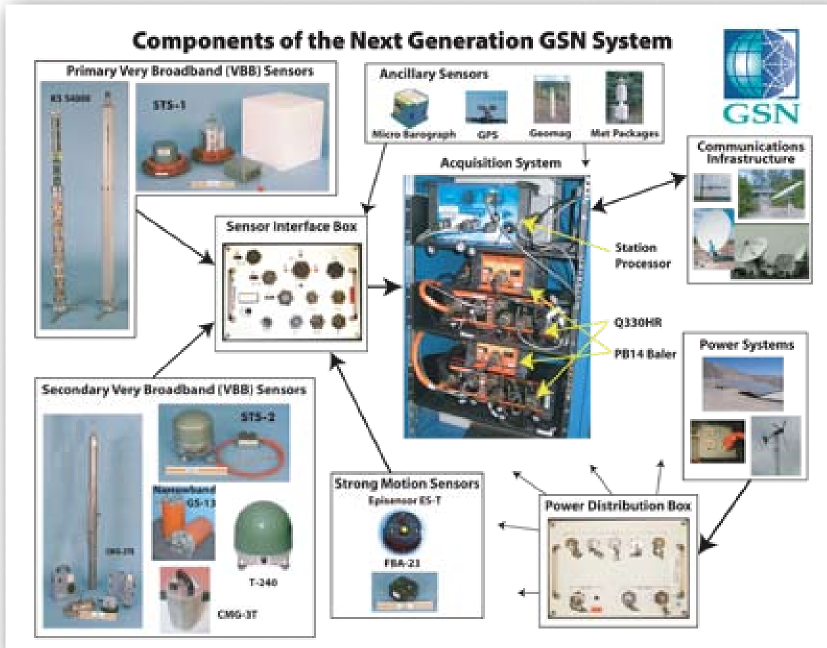
GSN has undertaken a systematic review of over 6,000 sensor-years of GSN seismometer failure and replacements rates. Based upon actual GSN statistics, the mean-time-between-replacement (MTBR) has been calculated for each sensor system. Note that this is not mean-time-between-failure (MTBF), because some sensors are replaced for reasons other than intrinsic technical failure; for example, for a lightning strike, the electronics may be harmed (sometimes affecting one sensor but not another at the same location, reflecting robustness of the electronics and luck). Thus, the replacement events take into account the real conditions in which the sensors are deployed throughout GSN, and reflect historical rates in dealing with both intrinsic and extrinsic factors. Expected yearly sensor replacement rates may be calculated by dividing the numbers of sensors deployed by their respective MTBR.

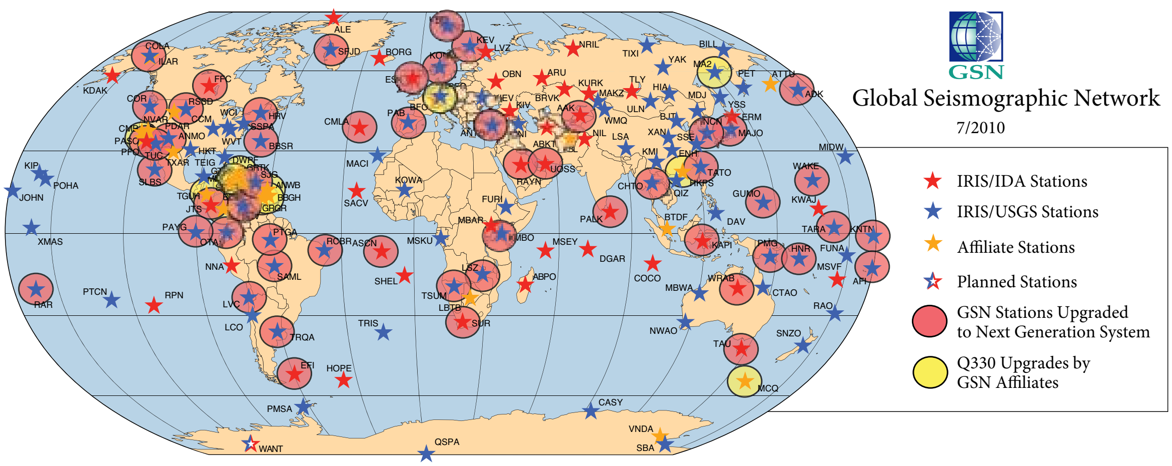
SENSOR	SENSOR YEARS	MTBR YEARS
STS-2	559	24.9
STS-1 per component	2928	49.9
KS54000	433	15.3
GS-13	546	485.4
FBA-23	1134	24.1
CMG-3T,3TB	412	16.6

For broadband sensors, the STS-1 and STS-2 have significantly better MTBR than the KS54000 and CMG sensors. The GS-13 is a narrow-band sensor with passive electronics, and is very robust. The FBA-23 is a strong-motion sensor.

THE NEXT GENERATION SYSTEM (NGS) FOR THE GSN

Based on the Quanterra Q330 HR data acquisition system, the next generation field system was co-designed by the USGS and IDA network operations center under the guidance of IRIS GSN management. This provides the GSN with a standardized, state-of-the-art recording system to optimize field operations and allow for more consistent and complete command and calibration of the GSN network. Rollout of the NGS is expected to take us through the proposed Cooperative Agreement.





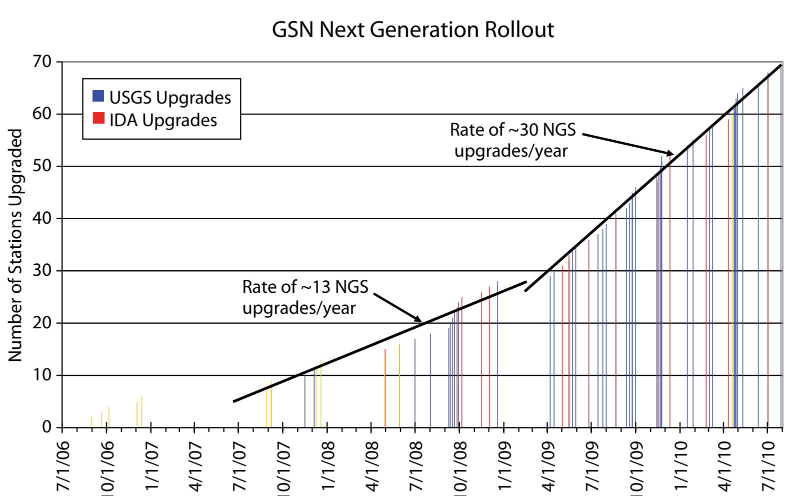


Figure A1.2. IDA field engineer installs the NGS equipment in a vault in Saudi Arabia (RAYN).

cannibalization (as seen with the legacy systems). Sufficient transition spares will need to be available. Assuming a "field-able" life cycle of about 12 years, our initial NGS installation in 2008 will be followed by a renewal in about 2020. Therefore, in the 2016–2017 time frame, GSN will need to review its design goals, draft new specifications, and begin the procurement process for the "next NGS." In the short term, maximum advantage of NGS is made in its rapid deployment throughout the network, which is taking place now. This creates efficiencies for GSN through standardization across the network, improved and automated system monitoring, remote calibration capabilities, and reduced troubleshooting requirements (complete system swaps for maintenance).

About 55% of the network will have been upgraded under this current Cooperative Agreement, and the remainder will take place during the years covered by this proposal. Repairs of the Q330HRs are outsourced to the manufacturer (MTBF is about 80 years, verified by experience in the 400-station USArray Transportable Array), saving GSN engineering staff resources for more productive O&M and data-quality functions.

In addition to sensors and NGS, ancillary equipment and material and supplies (items with individual costs < $5K) represent a significant portion of the total GSN equipment. These items range from communications and power infrastructure, to routine station supplies. They are not inventoried and tend to wear out much faster than major items. The long-term budgeting must accommodate these yearly expenditures.

When establishing GSN, a significant portion of the budget was dedicated to civil works and site preparations. Forty-five GSN installations were based on existing USGS or IDA facilities, many of which date to WWSSN installations of the 1960s. For many of the other 85 core GSN stations, the infrastructure was established substantially "from scratch." Costs varied significantly, depending upon the installation and location. New vault sites in Africa cost upwards of $245K, and remote borehole sites on islands cost $277K in 1995 dollars. Most costs were less than half of these extremes.

This infrastructure is significantly aging. Boreholes have been abandoned due to water leakage into sealed casing on both Midway and Johnston atolls, and to tectonic deformation of near-surface casing in Colombia. Some vaults built into rock outcrops (Mali and Gabon) or lava tubes (Canary Islands) for quiet conditions have turned out to have corrosive and/or high-temperature conditions (up to 50°C). The encroachment of civilization is producing higher noise levels (even at the South Pole). Hurricanes (Wake Island) and landslides (GSN affiliate in Singapore) have wrecked otherwise good sites. Even in cases where best practices were used in the initial site selection or where logistics dictated pragmatism, noise conditions at some GSN sites proved to be very high. Several GSN sites could benefit from relocations, including BILL in Siberia, KOWA in Mali, MSKU in Gabon, and NRIL in northern Russia. For a network of over 130 core stations, a proactive program of site improvements/upgrades will be necessary to address known issues as well as rarer (but not unexpected) catastrophic losses due to hurricanes, fires, and other hazards.

To sustain the GSN, long-term requirements in 2008 for replacing and modernizing equipment, plus upgrading site infrastructure was estimated to be ~$1.5M/year. Note that the 2009 stimulus funding enabled the GSN to "catch up" with many long-standing equipment needs, and to procure additional equipment for the coming years. Therefore, in the near-term, equipment needs are much more modest, as reflected in the 27-month budget. Further, GSN expects a number of ancillary equipment items to decrease in cost, yielding further savings. Nonetheless, long-term aggregate equipment and infrastructure needs must be monitored and projected to ensure a sustainable network. These costs are in addition to "fixed" costs for personnel, overhead, travel, shipping, telemetry, and stations stipends, which are typically considered to be the base O&M budget. As the NGS upgrades are completed, we will be assessing the personnel structure required in the shift from installations/upgrades to O&M and sustainment, and may redistribute personnel as necessary to assure high-quality data return in the most efficient manner. Aggregate, gross telemetry and stipends costs (2008) for GSN were about $400K and $500K, respectively. These costs do not include telemetry contributed by national (USGS ANSS and NOAA/NWS) and international partners (e.g., CTBTO, China, Russia, Australia). All of these costs are subject to inflation.

ACTIVITIES UNDER THE CURRENT COOPERATIVE AGREEMENT

TSUNAMI RESPONSE

The great Sumatra-Andaman earthquake and consequent Indian Ocean tsunami disaster of 2004 brought focus and resources to GSN as a key element of the international tsunami warning system. Real-time telemetry was expanded from 88% coverage to 96%, now 148 of the 154 current sites, and system robustness was improved with back-up communication links. The USGS established a nine-station Caribbean Network, which is affiliated with GSN, and brings enhanced coverage between North and South America. Via a Memorandum of Understanding with IRIS, telemetry collaboration with NOAA increased with 10 sites now satellite-linked directly to the Pacific Tsunami Warning Center in Hawaii. The network links NSF, USGS, and NOAA, recognized in law in the Tsunami Warning and Education Act of 2006.

CORE NETWORK

In parallel with the tsunami augmentation, the basic global coverage plan was completed with the installation of six new stations—TARA and KNTN in the Republic of Kiribati (central tropical Pacific Ocean); ABPO Madagascar; SLBS Mexico; MACI Canary Islands; and UOSS United Arab Emirates—plus Affiliates KBL Afghanistan and HKPS Hong Kong. As of 2010, 23 affiliate stations join a core network of 80 USGS-operated, 41 IDA-operated, and 10 China-operated stations (collaborating with the USGS). In addition, the complement of installed microbarographs was expanded from 40 to 70 stations, and participation in the International Monitoring System (IMS) increased from 23 stations to 33 core stations and seven affiliate stations.

Figure A1.3. USGS-Honeywell field engineer Jared Anderson takes and opportunity to teach basic seismology to the school children on Kanton, Republic of Kiribati (GSN station KNTN).

PERFORMANCE REVIEW

A comprehensive review of agency usage and performance of core stations concluded that every active station is routinely used by some monitoring agency and that even island sites, which tend to be the noisiest stations, are very valuable to the tsunami warning centers. Agency metrics included importance, quality, and usage by the Pacific and the West Coast and Alaska Tsunami Warning Centers, the *Air Force Technical Applications Center (AFTAC)*, the IMS, and the National Earthquake Information Center (NEIC) in determining epicenters and W-phase earthquake moments. Data performance metrics included vertical and horizontal noise levels at 1 Hz, 300 sec, and broadband. A metric of contribution to global coverage is based upon distance to the nearest neighboring station. A survey of the scientific community ranked GSN stations for merit/importance in scientific studies. These metrics now serve as an objective basis for decisions regarding station relocation/closure and commitment, prioritization, and allocation of GSN resources.

INTERNATIONAL COLLABORATIONS

New partnerships with Spanish, German, Australian, and Russian organizations exemplify GSN's continuous engagement in international collaboration. The Instituto Geographico Nacional (IGN) of Spain has collaborated at a new GSN site MACI Canary Islands (a relocation from the prior site at TBT), providing the STS-1 sensors, data acquisition, and telemetry as part of their local network, and primary maintenance responsibilities. Bundesanstalt für Geowissenschaften und Rohstoffe upgraded the DAS at Grafenberg and took primary responsibility for maintenance, while GeoForschungsZentrum Potsdam (GFZ) installed a geomagnetic observatory next on St. Helena Island in the South Atlantic that shares the communications circuit for station SHEL. Geosciences Australia has undertaken expanded responsibilities and provides major maintenance assistance in and around Australia, extending to sites on Papua New Guinea, Solomon Islands, Fiji, Tuvalu, Rarotonga, and Kiribati that are crucial to Australian tsunami warning. The Russian Academy of Sciences' Geophysical Survey (GS-RAS) in Obninsk now provides for all telemetry within Russia, ensures data flow based on a new intergovernmental MOU, and has started purchasing, importing and installing NGS systems from IRIS—including Q330 DASs, STS-2 seismometers, and STS-1 electronics—expanding their role to O&M of all GSN stations in Russia and opening possibilities for more instrumentation upgrades and data exchange with the Russian National Network.

TELEMETRY

In the past few years, new communications systems were installed in FURI Ethiopia, RAYN Saudi Arabia, MSVF Fiji, and JOHN Johnston Atoll, and system robustness was improved by providing for redundant links at key sites in the Pacific. As mentioned above, the GS-RAS has taken over the Russian telemetry links and now fully funds the data flow. A substantial component of this expansion was funded by the USGS following the Sumatra earthquake. The telecommunications infrastructure is diverse, with portions funded by IRIS, USGS, Russia, China, Australia, the Department of Defense, NOAA, and the CTBTO, with Internet connections provided by local hosts. Although the diverse telemetry topology adds to the management burden, the system minimizes costs as well as maximizes robustness by not having all communications routed through a single point of failure.

SEISMIC INSTRUMENTATION

IRIS completed a comprehensive, multiyear process to evaluate, test, select, and procure the next-generation GSN DAS, and selected the low-power systems (<10W) Quanterra Q330HR to improve robustness in remote locations and offer remote calibration via the telemetry link. A standard installation allows resources to be shared across the entire GSN, optimizing the equipment depots at both network operations facilities. By the end of this proposed Cooperative Agreement, DASs will have been fielded across GSN, freeing resources previously tied down to obsolete equipment.

Long-term changes in the response of some Streckeisen STS-1 sensors, the primary GSN vault sensor that has not been produced 1996, has raised concerns. Further testing of STS-1 electronics has shown that the aging systems may be adversely affected by humidity, with amplitude-dependent effects in some frequency bands. This nonlinearity was not easily detectable with our past quality assurance techniques, and thus, new quality metrics are being implemented to allow us to track sensor aging. In addition, with funding from IRIS in 2006, Metrozet LLC and UC Berkeley successfully developed new feedback electronics for the STS-1, which is now in production, and is being fielded and used at stations of the GSN and other FDSN networks. With the lack of an immediate replacement for the STS-1 mechanical assembly, improved installation techniques for secondary sensors are providing for a better long-period response, enabling the replacement and relocation of STS-1s at sites that have relatively high background noise, and improving the relative performance of the secondary sensor at other sites where both are installed.

Current GSN borehole sensors have been problematic but, because replacement and repair costs are high, IRIS is focusing on a future sensor. A revised borehole seismometer specification is being prepared in consultation with the IRIS Instrumentation Committee and AFTAC/DoD, which also has substantial needs for borehole instrumentation, and IRIS plans to work with potential manufacturers to test and evaluate new sensors. Under the new IRIS Instrumentation Services structure, GSN will coordinate with PASSCAL and USArray in this and other areas related to the exploration of new sensor technology.

CALIBRATION, AZIMUTH, AND DATA QUALITY

Degradation of the STS-1 electronics and the past QC system's inability to measure this decay brought into focus the need to place data quality on a par with data availability as a true measure of GSN's performance. Calibrations performed on initial site installation and during site visits were augmented with remote calibrations where the DAS, telemetry link, and local hosts were capable. The NGS systems have remote calibration capabilities, so with the completion of the NGS upgrade, the entire GSN can be routinely calibrated (with local political permission, in some cases). Apparent problems noted (Ekström et al., 2005, *Seismological Research Letters,* doi:10.1785/gssrl.79.4.554) regarding instrument sensitivity defined a need for absolute field calibration to complement and verify independent checks based on earthquake free oscillation modal data and tidal amplitudes (Davis and Berger, 2007, *Seismological Research Letters*, doi: 10.1785/gssrl.78.4.454; Davis et al., 2005, *Seismological Research Letters*, doi:10.1785/gssrl.76.6.678).

At the same time, subtle azimuthal errors in sensor orientation were being determined and refined using the data themselves and measures of great circle paths from many earthquakes. In response, network operators defined rigorous best practices for location, orientation, and calibration of sensors using field kits that included a reference broadband seismometer, precise azimuth determination equipment, and a well-calibrated DAS. The kit has been in use during site visits since 2008, and the reference sensor is absolutely calibrated on a shake table before and on return from each visit. Network operators are systematically assaying site infrastructure that may affect apparent response to determine and plan long-term site refurbishment needs.

In 2009, GSN adopted a new calibration policy wherein absolute calibrations would take place during field visits (both before and after major station upgrades), and yearly relative calibrations would take place at all sites where both telemetry and local DAS permitted remote calibrations. In 2009 during the initiation of DAS upgrades, 27 absolute calibrations and 66 relative calibrations took place, building upon historical calibrations and network-wide calibration efforts during

2003–2006. Procedures for calibration and updating metadata are being reviewed and standardized among the network operators as part of a pan-IRIS assessment of data quality.

As a result of concerns about data quality related to the aging of the STS-1 sensors and the tracking of metadata, the IRIS Board established a GSN Data Quality Panel in 2010 to assess the quality of GSN data, review current quality control procedures, and make recommendations for implementation of standard metrics and practices to measure and report on GSN waveform quality. Based on the recommendations of the Panel, the GSN Operations Group will expand the routine quality-control procedures that are implemented by the network operators, routinely tracked, and published on IRIS web sites. The goal is to provide both the scientific user and network operator the same view of data quality so that each may effectively use the open information, and to create an archive of the state of data quality for a sensor. GSN will continue to work with the Lamont Waveform Quality Center (WQC) to track station performance and review prior calibration and data quality, supported by QC analysts collaborating between the IRIS DMS and GSN. Collection of data problem reports has been reinstituted, and the scientific community has been encouraged to offer their own problem assessments at GSN stations.

GSN AUGMENTATION FUNDING 2009

Both NSF and USGS received substantial additional funding in FY09 through the American Recovery and Reinvestment Act of 2009 (ARRA), which has led to over $9M supplementary funding for GSN. Through coordinated efforts between USGS and IRIS/NSF, a comprehensive, integrated plan was developed, encompassing both ASL and IDA. Funds for a broad renewal of GSN equipment focused on immediate procurements, including all DASs needed to complete the GSN upgrade, secondary broadband sensors, replacement FBE systems, and many other urgent needs. The supplementary funding also accelerated deployment of NGSs and sensors. During 2009, 25 stations were upgraded, electronics were replaced in 12 STS-1s, and 12 secondary broadband sensors were replaced. Through the June 2011, well over half of the core GSN will have been upgraded and enhanced.

USGS GSN FUNDING

Funding by the USGS has substantially increased in recent years. As a part of the 2005 Tsunami Supplement, the USGS received funds for expanding GSN's real-time telemetry infrastructure at stations operated by both ASL and IDA, for the installation of the nine-station Caribbean Network (Affiliated with GSN), and for a step increase in their base budget (about $600K) to operate and maintain these additional facilities. The university community has worked closely with the USGS in the past few years, stressing the importance of the GSN as a multi-use, multi-agency facility, and encouraging consideration of funding increases for the USGS GSN line in the Department of Interior budget. This request has resonated with Congress, and funding added in FY08 ($500K) and FY09 (~$1M), has now been adopted by the Administration, increasing the base of the USGS GSN program in FY10. With each of these increases, the USGS has stepped forward and taken an equal role in funding GSN equipment and upgrades, which heretofore had been the role of NSF/IRIS. The more equitable collaboration between USGS and NSF/IRIS is a new paradigm for the GSN, with both parties taking primary roles for their network operations and also jointly funding the network to take best advantage of resources and capabilities. IRIS now has more latitude to focus GSN funds toward new ways to improve the GSN for science and to continue its O&M role through IDA.

NEW OPPORTUNITIES AND DIRECTIONS

The next 27 months will see the culmination of the first major upgrade cycle in GSN equipment since the initial installation of the network. Through funding supplements related to the federal stimulus package in 2009 from both NSF and from USGS, GSN is being transformed from a network that has been focused on basic operations and maintenance of an aging equipment base, to one focused on sustaining a standardized system of state-of-the-art equipment, incorporating efficiencies in operations, maintenance, monitoring, and quality. The most important task in the short term is to get the new equipment fielded so that the network may begin to accrue those benefits. GSN will maintain the installation rates of NGS and sensors that were accelerated in 2009. Through this effort, the refreshed network will also be able to address many data-quality issues that suffered from an inadequate equipment replacement budget, bringing GSN data quality back to the forefront. At the same time, GSN looks toward exciting new directions to reinforce its successes both as a network and as an integral program for global seismology. Toward this end, GSN will take stock of the station infrastructure and test

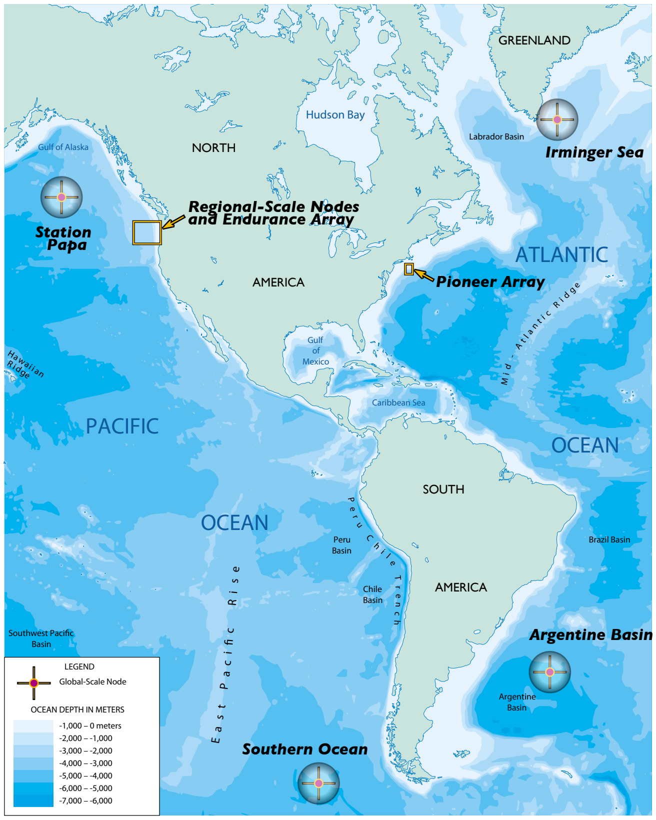


Figure A1.4. Possible locations for the OOI global buoys.

new prototype primary sensors, will review with the community advances in science that may be made through the implementation and use of arrays, will engage through FDSN a systematic assay of national broadband networks and their respective means where the international community may gain access to these data, and actively engage with the ocean seismic community through the Ocean Observing Initiative.

Looking forward, GSN will be renewing and invigorating techniques and procedures to ensure the GSN dataset is of the highest quality. The network is in place, and has captured with full fidelity the third and fifth largest earthquakes ever measured since the dawn of instrumental seismology. GSN real-time data are used at more than tenfold their acquisition rate. Operationally, the GSN envisioned in the mid 1980s is now in place. The new dimension for growth is quality. This focus extends beyond instrumentation and infrastructure. GSN is a champion of open data, and must also embody the principle of open information regarding its data quality. Here, GSN leadership can potentially bring about improved data-quality practices beyond GSN.

NETWORK

The 154-station GSN multi-agency network model with IRIS management coordinating the primary network operators USGS/ASL (IU, IC subnetworks) and IRIS/IDA (II), and independent GSN Affiliates, has proven to be a robust collaboration. Funding and resources have been effectively shared for the broad benefit of GSN. IRIS continues to fund UCSD/IDA. With the increase in the USGS base budget for GSN beginning in 2009, USGS funding for ASL's components of GSN have expanded beyond O&M to equipment, installations, and station upgrades—many which were funded by IRIS/NSF under the prior Cooperative Agreement. Nonetheless, whereas both IRIS/NSF and ASL/USGS have parallel funding for their respective GSN components, successful collaboration between IRIS/NSF and ASL/USGS seen during the ~$9M federal stimulus funding in 2009 underscores the efficiencies achieved in combining and collaborating resources. In this regard, the IRIS GSN budget continues some support for ASL activities that may be more efficiently funded through IRIS. Complementary to this, USGS funds will be coordinated with pan-GSN activities.

The GSN Standing Committee (GSNSC) provides oversight for both IRIS/NSF and USGS, under the NSF-USGS-IRIS MOU Annex. The IRIS and USGS GSN program managers have parallel responsibilities to coordinate GSN for IRIS/NSF and USGS, respectively. IRIS funds a GSN office, and provides support for the GSNSC, and for GSN management. GSN management also has roles and responsibilities for IRIS polar activities (including the Greenland Ice Sheet Monitoring Network).

The completion of the NGS upgrade effort is the crucial foundation for the GSN's long-term operation and maintenance efficiency and improved data quality. To accelerate the rate of upgrade for the network, both ASL and IDA augmented their personnel (3 and 1 FTE, respectively) in support of the field activities and station maintenance as well as enhancement to their shipping and travel funds to allow more station visits. Both groups are sustaining this level of effort throughout the 27 months covered by this proposal in order to finish upgrades as expeditiously as possible. All IRIS/IDA upgrades are planned for completion by 2013, barring difficulties with Russia. ASL upgrades are planned for completion by 2015, barring difficulties with Russia and China.

Network standardization improves functionality and creates efficiencies. Equipment standardization will permit ASL and IDA to coordinate and collaborate on station maintenance, which was not possible before. Within the context of such GSN collaboration, the network configuration is being analyzed with a view toward making more efficient use of logistics, shared resources, and personnel. Long-term perspectives for possible restructuring GSN will take into close account the important relationships with station hosts. Further, when GSN equipment is standard across their territory, large national partners (e.g., Russia and Australia) may take a greater role in station operation and maintenance. On a single station, case-by-case basis, international hosts may wish to take greater responsibility, or even full responsibility, for local GSN stations. These arrangements and discussions will be constructively met, and encouraged insofar as GSN data quality may be assured and the design goals of the GSN can continue to be met.

STATION PERFORMANCE

GSN (both IRIS/USGS and IRIS/IDA) operated with about 85% data availability, prior to the funding augmentation in 2009. With the new, low-power NGS, and adequate stock of secondary sensors and STS-1 electronics, we anticipate data availability increasing toward our 90% target. New GSN data-quality metrics are being developed to assess the variance of sensor data from our published design goals, and include noise level, linearity, calibration accuracy, and orientation. These web-published metrics, uniformly applied across the core network, will not only offer a clear status and history of sensor data quality for the scientist using the data, but also better enable GSN network operators to monitor quality, to bring engineering expertise to problems identified, and for making decisions on the allocation of resources for field repairs and site visits. This data-quality transparency for the community enhances the GSN data, and offers leadership to other international networks for raising the global awareness of data quality.

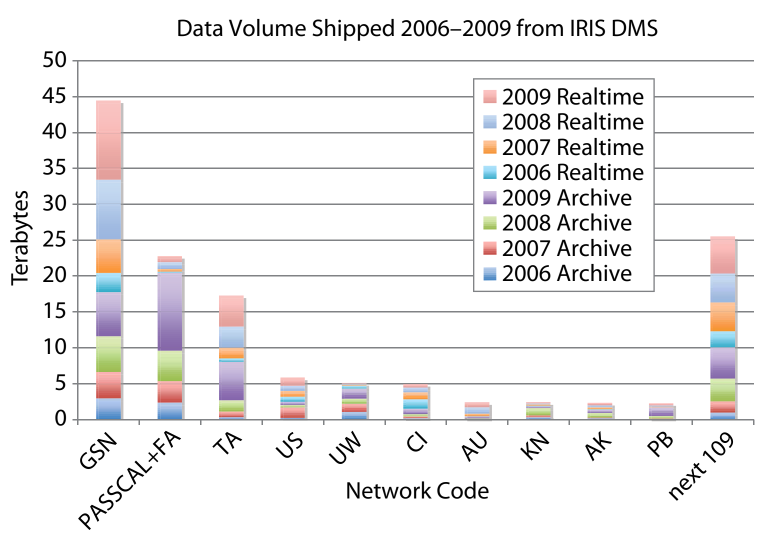
DATA QUALITY

Informed by the recommendations of the GSN Data Quality Panel (expected the fall 2010), quality metrics and assessment tools will continue to be developed and utilized to share information on data quality with both network operators and data users. Additional resources will be coordinated with ASL to ensure close collaboration with the USGS. This enhanced data-quality focus includes reviewing the historic data archive and metadata, end-to-end tracking of data problems reports, implementing new and improved tools for measuring and assuring data quality, tracking and publishing QC metrics, and publishing sensor problems and calibrations on a GSN/DMS web site. In addition, the data problem report process will be revitalized along with the development of a data user interface to allow feedback directly from the data users to the Operations Group. The GSN Operations Group will continue to coordinate with the Lamont Waveform Quality Center on metrics, techniques, and quality-related information. Working through the new IRIS Instrumentation Services and Data Services structure, there will be a renewed

GSN DATA USE

Data from the Global Seismographic Network are the most widely accessed dataset in the IRIS Data Management System, with over 44 Terabytes (TB) of data shipped in 2006–2009, both in real time and from the archive (see figure). Over 11 TB were distributed in real time in 2009 by DMS. Nonetheless, GSN data are also distributed in real time to a broad spectrum of users separate from the DMS distribution.

Many networks or large data users access GSN data directly from USGS and UCSD data collection centers, via tsunami warning centers, through software operating at various seismic networks, or from the GSN station itself. These real-time users include USGS/NEIC, U.S. and international tsunami warning centers, Global CMT, CTBTO IMS, and national networks and organizations in Australia, Austria, Canada, Chile, China, Colombia, Czech Republic, Dominican Republic, El Salvador, France, Germany, Guatemala, Hong Kong, Iceland, Indonesia, Italy, Japan, Kuwait, Malaysia, Mauritius, Mexico, Morocco, Netherlands, Puerto Rico, Nicaragua, Norway, Oman, Philippines, Romania, Russia, Singapore, Spain, Sweden, Taiwan, Thailand, Turkey, United Arab Emirates, United Kingdom, and 31 local station hosts, and others. Tracking the amount of data requires a certain amount of detective work and engagement in correspondence with international users.



An estimate of GSN real-time data usage not distributed by DMS is about 6.9 TB/yr, or about half of the DMS rate. This estimate does not count multiple uses of GSN data within an organization. The estimated total GSN real-time data usage rate (circa 2010) is therefore about 18 TB/year, compared with a nominal GSN data logger rate of about 1.1 TB/year.

and increased collaboration between the GSN and the DMS (through the Operator's DCC and the DMC) to continue to produce, enhance, and automate quality metrics for GSN data that assure the seismological community of current state of the GSN dataset.

EQUIPMENT

GSN's near-term equipment needs were substantially fulfilled by the funding augmentation in 2009. Procurement of secondary sensors, based upon GSN historic replacement rates, will continue to ensure that adequate stocks are maintained. NGS failures will be met through repairs based upon known USArray Transportable Array repair rates. Ancillary small equipment for station maintenance must also be budgeted. IRIS and USGS will coordinate these purchases between IDA and ASL, in proportion to relative numbers of GSN stations.

DEVELOPING NEW PRIMARY SENSORS

It is critically important that replacements are developed and tested for the GSN primary broadband sensors—the STS-1 (surface) and KS-54000 (borehole). Additional urgency for this task has come from recent analyses by the Waveform Quality Center, which indicates that the Metrozet E300 does not solve all of the issues with the STS-1. High failure rates of the KS-54000 have caused the network operators to cease purchasing them. GSN quality will continue to deteriorate if these problems are not solved in the coming years.

During the term of this proposal, GSN proposes to purchase and field test several prototype primary sensors. Both Metrozet and USCD are now developing prototypes that may approach STS-1-quality. New broadband sensors are being offered by several manufacturers, with the potential to be packaged for borehole deployment. USGS is supporting development in FY11 of a borehole version of the UCSD optical seismometer, which presents a new option for borehole installations. To actively engage the market for primary sensors, this proposal requests funding for instrument manufacturer engagement, procurement, and testing. The path forward will stimulate production of new GSN primary sensors, which may then be proposed for volume procurement in the five years hence.

NEW STATIONS

Whereas GSN now has achieved its goal of global coverage, there are still gaps in geographic coverage in a few subcontinental areas (e.g., North Africa, India, Nepal) and, of course, in the broad ocean area. There are ongoing discussions with Libya and Egypt (North Africa), and Italy (for a site near Mt. Everest), and there are siting possibilities for West Antarctica following PoleNet temporary deployments. Engagement continues quietly with India. In addition, there are occasionally favorable opportunities to relocate, or completely re-install an existing station to be responsive to changing political situations or natural disasters (recall past experience with our stations in Colombia, Canary Islands, and Wake Atoll). In order to fully leverage such opportunities, GSN requests $250K funding for the equipment necessary for a new site, civil works for site preparation, and installation costs.

SITE INFRASTRUCTURE

Aging of the network is also reflected in its site infrastructure, including vaults, piers, boreholes, buildings, power, and telemetry equipment. For instance, WWSSN vaults used by GSN are nearly 50 years old. Some of this infrastructure directly impacts GSN data quality. As noted earlier, as part of NGS roll out, GSN is systematically assessing the condition of its infrastructure. Annual funding is requested to repair site infrastructure to coordinate effectively with ongoing field activities.

POLAR ACTIVITIES

GSN management will continue its active engagement in polar activities in collaboration with PASSCAL (discussed in the section on Polar Support Services), both through the international collaboration in the GLISN project in Greenland, as well through development of long-term sites in West Antarctica for monitoring its ice sheet. Coordination of the specialized equipment and installation techniques between the two core IRIS programs is important to ensure high quality and data return in these challenging environments.

Figure A1.5. GSN station AFI (Afiamalu, Samoa) vault infrastructure issues (courtesy of ASL/USGS).

NEW DIRECTIONS

Three exciting new directions are proposed for GSN, which both serve to expand the capabilities for GSN science and naturally link with existing GSN activities: incorporating arrays into GSN, working with FDSN to expand and enhance international data exchange, and engaging with the Ocean Observing Initiative to provide GSN-quality sensors for seafloor deployment.

Seismic Arrays

The "Seismological Grand Challenges" report recognizes that seismic arrays offer great potential for resolving important questions regarding such diverse topics as the nature of the lithosphere-asthenosphere boundary, how temperature and compositional variations control mantle and core convection, and how Earth's internal boundaries are affected by dynamics. Moreover, arrays can be used to greatly improve earthquake detection capabilities on a global scale. While events as large as magnitude 5.5 can hide from current networks, a global array of arrays would lower detection thresholds by one to two magnitude units. Complete and accurate earthquake catalogs are a fundamental dataset for addressing several of the Grand Challenges. Whereas some of these questions may be answered with temporary PASSCAL portable array deployments, the others will require long-term to semi-permanent monitoring and hence fit within a framework that bridges the gap between GSN's permanent global observatories and PASSCAL's higher-resolution temporary deployments.

Arrays have several advantages over three-component stations. An array provides directional information on an arriving wavefield, including both azimuth and "slowness" (inverse apparent velocity of the wave), and individual sensor channels can be combined as a beam to improve signal to noise and to focus on aspects of the wavefield. There are diverse designs for arrays, depending upon the particular purpose, which include high-frequency and broadband elements, as well as three-component and only vertical elements. The aperture (array width) and the organization and spacing of array elements can enhance or attenuate features of the wavefield being viewed. Whereas a GSN station occupies a relatively small footprint, extending this framework for an array may be constrained by local host considerations and can limit collocation with existing GSN sites. Finally, the array is a passive sensor—like the GSN station, it records seismic phenomena that propagate to it.

Four Affiliate arrays are part of GSN, installed and operated by AFTAC or DOE/Southern Methodist University, which are also IMS arrays. There are 18 additional IMS primary arrays, but unfortunately the CTBTO confidential data policy limits scientific community access to these valuable resources. Open access has been obtained on a bilateral basis with Canada, Australia, Germany, Kazahkstan, and Norway. Efforts continue for more open release of array data from the other 11 IMS primary arrays, in coordination with FDSN. Nonetheless, most of these arrays have been narrowly designed for their sole purpose—to detect and monitor nuclear explosions. The Southern Hemisphere has only two Australian arrays. "Sweet-spots" for viewing a particular feature may require an array installed at an entirely new site. To use the array for specific imaging of Earth structure, the geometry of the earthquake sources, the array, and the lithosphere-asthenosphere-mantle-core structures to be illuminated must be refined.

IRIS proposes to study these broad scientific and technical questions in workshops, and perform a pilot experiment during the coming 27 months, in order to reach a consensus with the scientific community of the best course forward. The focus of these two workshops are: (1) the specific scientific objectives and priorities for augmenting GSN with fixed arrays, and (2) the technical plan (array geometry, siting, instrumentation, and international coordination) needed to achieve the scientific objectives. The pilot experiment will demonstrate with an existing array—for example, the SIEDCAR experiment (Seismic Investigation of Edge Driven Convection) and the High Lava Plains (HLP) project—the capability for resolving targets of future arrays. Exploration of the technical aspects of array development will be coordinated through the new IRIS Instrumentation Services structure to ensure that these effort draw on the extensive experience of PASSCAL and USArray/TA as well as GSN. Because the science will drive the array design(s), the second workshop must await the outcome of the first.

Enhancing International Data Exchange

IRIS is proactive in advocating for open data sharing, and GSN is an example of the practice. GSN openness has generated substantial goodwill globally. Many organizations that never openly shared data internationally now provide data to the IRIS DMS, in part because of their own active usage of the open GSN data. Two such examples are the Japan Meteorological Agency (JMA) and Malaysian Network—both have opened real-time access to seven of their broadband stations.

GSN actively participates in the FDSN working group on station siting, which attempts to keep an active inventory of all broadband networks participating in FDSN, as well as the means for accessing data. FDSN has been very successful in bringing together the international seismic community. However, as an unfunded federation, the "simple" task of listing all broadband stations lies beyond current abilities of the volunteer organization. Moreover, there are also many nations that operate broadband networks (e.g., installed by Kinemetrics, Nanometrics, and others), which do not openly participate in FDSN. Although attempts have been made to compile inventories of broadband seismic stations in Europe by ORFEUS, and in the United States by NEIC, there is no substantial global inventory of broadband stations.

To open up new sources of seismic data, we first must determine what is there. Then, we need to determine how a scientist can request data access. These two simple steps are a substantial undertaking, requiring engaged discussions with networks worldwide. Such engagement has as a prerequisite a friendly reception. As a U.S. scientific entity, IRIS and GSN face the political baggage (both good and bad) carried by the United States in its global relations. However, FDSN carries no such baggage as an international organization of 52 nations. Its credentials as a Commission of the International Association of Seismology and Physics of the Earth's Interior (IASPEI) are impeccable. Further, FDSN's Terms of Reference provide for *pursuing free and open access to data*. Nonetheless, FDSN has no resources for this task. The International Seismological Centre (ISC) has an internationally recognized office, but does not currently address waveform data exchange.

Therefore, IRIS proposes to work with FDSN and ISC to fund a person to lead this task. An individual is needed with scientific credentials and with a good sense of diplomacy and skills in database management. The task deliverables are a substantial inventory of all broadband stations worldwide (including sensor characteristics, updated yearly), and documentation of the methods and procedures for accessing data. Both FDSN and ISC chairs have been approached, and are receptive to the idea. Some FDSN members have already indicated interest in collaborative funding for such a position.

This activity is being coordinated with the IRIS DMS role in archiving and exchanging data between data centers. As is their prerogative, some networks do not exchange data. However, they may provide data to an individual scientist. Making known what data exists and how it may be accessed is the initial step—that in some instances may lead to a broader exchange with a data center.

Building Toward Collaboration with the Ocean Observatories Initiative

During 2011–2013, the Ocean Observatories Initiative (OOI) will begin to construct and install a new generation of permanent observatories in the ocean with real-time telemetry that will revolutionize oceanography. The particular focus of the OOI Global Buoy program on high-latitude sites such as the Southern Ocean is of great interest to the GSNSC. While the current OOI science plan does not include seismometers at the Global Buoy sites, OOI still represents an important opportunity for GSN. Expanding GSN coverage into the ocean is a requirement if it is to achieve its original design goals and to provide the uniform coverage necessary for many science and monitoring objectives. The three locations that are of most interest to GSN due to their remoteness are the Southeast Pacific site (55°S, 90°W), the Argentine Basin site (42°S, 42°W), and Station Papa (50°N, 90°W) in the Northeast Pacific. Both the Southeast Pacific Ocean and Argentine Basin sites are located approximately 1500 km from shore and ~1700–1900 km from the nearest GSN station. If the Southeast Pacific site already existed, it would have provided the first seismograms west of the trench for the 2010 Mw 8.8 Chile earthquake.

During 2011–2013, the GSNSC will initiate a working group to develop a detailed plan for adding broadband seismic instruments to the OOI global buoys that can be incorporated into the following IRIS five-year proposal. Because the instruments will be telemetered and likely require burial, we will not be able to use the instruments currently in the national Ocean Bottom Seismometer Instrument Pool (OBSIP) directly. However, the instrumentation groups within OBSIP have already demonstrated most of the technical capabilities required for installing a buried broadband ocean bottom seismometer with acoustic telemetry to the global OOI buoys. Of particular concern will be the quality of the horizontal component data that are often extremely poor at frequencies <1 Hz for freefall OBS deployments. However, the Ocean Seismic Network (OSN) Pilot Experiment demonstrated that even shallow burial of the sensor pressure housing greatly reduces current-generated tilt noise. Because most of OOI cruises will likely not involve a remotely operated vehicle (ROV), any OBS system will require the ability to bury the sensor without an ROV. This type of technology only exists as a prototype at present. GSN will invite proposals from OBSIP groups for a subcontract to test a prototype burial system in a deepwater environment during 2011–2013. Through the combined efforts of the working group and the field testing of a burial system(s) by OBSIP groups, GSN will be well positioned to begin filling the current gaps in the ocean as part of the five-year IRIS proposal to be submitted in 2013.

2 | PROGRAM FOR ARRAY SEISMIC STUDIES OF THE CONTINENTAL LITHOSPHERE

HISTORICAL CONTEXT OF CURRENT OPERATIONS

The Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) provides and supports a range of portable seismographic instrumentation and expertise to diverse scientific and educational communities. Two basic IRIS concepts—access to professionally supported, state-of-the art equipment and archived, standardized data—revolutionized the way in which seismological research that incorporates temporary instrumentation is practiced at U.S. research institutions. By integrating planning, logistical, instrumentation, and engineering services, and supporting these efforts with full-time professional staff, IRIS has enabled the seismology community to mount hundreds of large-scale experiments throughout the United States and around the globe at scales far exceeding the capabilities of individual research groups. Individual scientists and project teams can now focus on optimizing science productivity, rather than supporting basic technology and engineering. Small departments and institutions can now compete with large ones on an equal footing in instrumentation capabilities. Scientists working outside of traditional seismological subfields now have the ability to undertake new and multidisciplinary investigations. Standardized equipment and data formats greatly advanced long-term data archiving and data re-use for novel purposes.

PASSCAL has also influenced academic seismology in all parts of the world explored by U.S. seismologists, and on many occasions enabled IRIS to spur or augment international collaborations by providing significant instrumentation and engineering. Many of the standards and facilities pioneered by IRIS for instrumentation and data collection, archival, and open exchange have been adopted by permanent networks and other groups in the United States and by seismological networks and organizations worldwide. Other seismological and nonseismological data collection groups in the United States have embraced open data, and obligatory data archival requirements and standards have increasingly been stipulated by federal agencies. Internationally, many portable seismograph facilities have adopted similar models for their operations.

THE INSTRUMENT POOL

When IRIS was established in 1984, the goals for PASSCAL were to develop, acquire, and maintain a new generation of portable instruments for seismic studies of the crust and lithosphere, with an initial target of 6000 data-acquisition channels. During the first IRIS/NSF Cooperative Agreement, the primary emphasis was on the careful specification of the design goals, and instrument development and testing. Three technological developments between 1985 and 1995 were critical to the success of portable array seismology: the

Figure A2.1. Photo of the PASSCAL Instrumentation Center at New Mexico Tech in Socorro, NM.

Table A2.1. Inventory of equipment.

	PASSCAL	Polar	USArray FA	USArray TA	RAMP
Datalogger 3-channel	875	44	472	438	
Datalogger 6-channel					10
Datalogger 1-Channel	980		1699		
Broadband Sensor	525	44	346	459	
Intermediate-Period Sensor	142	6			10
Short-period sensor	10		111		
High-frequency geophone	772				
Accelerometer	10		20		10
Multi-channel	14				

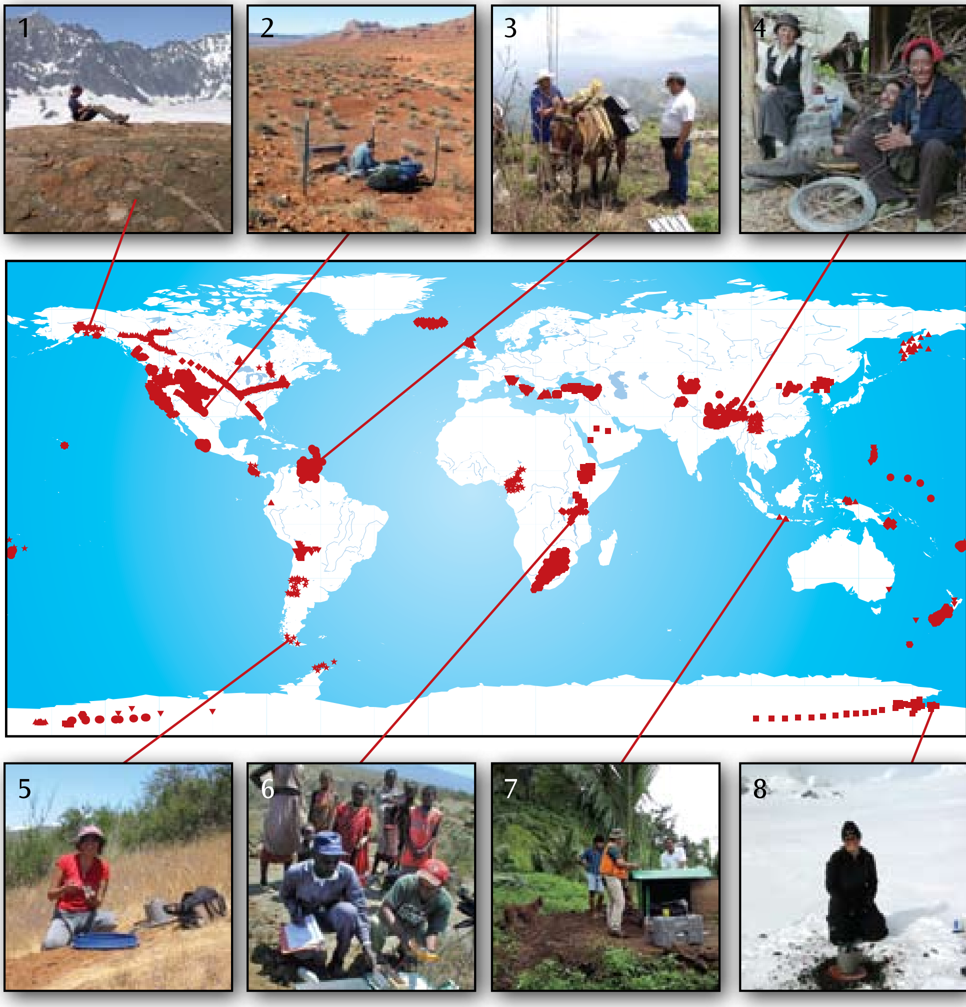


Figure A2.2. Global extent of station coverage for the history of the PASSCAL program, now totaling more than 3800 stations. PHOTOS. (1) Alaska. STEEP experiment. (2) La RISTRA, New Mexico. (3) Venezuela. Transporting gear the old fashioned way. (4) Tibet. Locals help with installation of a station. (5) Chile. Installing an intermediate period sensor. (6) Kenya. A short period station being serviced while local Masai look on. (7) Tiwi. Specialized enclosure for a rainy environment. (8) Mt. Erebus. An intermediate period sensor is installed directly onto the bedrock flanking the volcano.

development of low-power, portable, broadband force-feedback sensors; the availability of highly accurate GPS absolute-time-base clocks; and the advent of compact, high-capacity hard disks. An initial purchase of 35 systems grew by 1995 to a pool of more than 100 broadband instruments that were used primarily in passive-source experiments.

Design of instruments to support controlled-source experiments and rapid deployment for earthquake aftershock studies began in 1991, and by 1995 almost 300 of these instruments were available. The instruments used in controlled-source experiments also included 200 seismic group recorders (SGRs) donated by AMOCO and reconditioned for crustal studies. A new generation of active-source instruments, "Texans," were developed by a corporate-university partnership in Texas with funds the Texas state government. Procurement of Texans began in 1999, and the SGRs were retired over three years.

Starting in 2002, the Department of Energy provided funds to replace the original data acquisition systems, which were becoming aged and failure prone, with modern systems. The new systems incorporate the latest technologies from the computer industry. Consequently, they require much less power, have higher recording capacities than the first-generation instruments, use modern memory components, and are configured to operate with a number of communication systems as either serial devices or TCP/IP nodes. All of the older recorders have now been retired from use in temporary deployments.

The next few years promise to be equally exciting. By the end of this Cooperative Agreement, we anticipate that there will be designs and prototypes for a whole new generation of data recorders and sensors that will be smaller, lower power, and capable of operating in extreme environments for extended time periods. Communication technology is changing so fast that the ability to connect to the Internet from any location may truly exist.

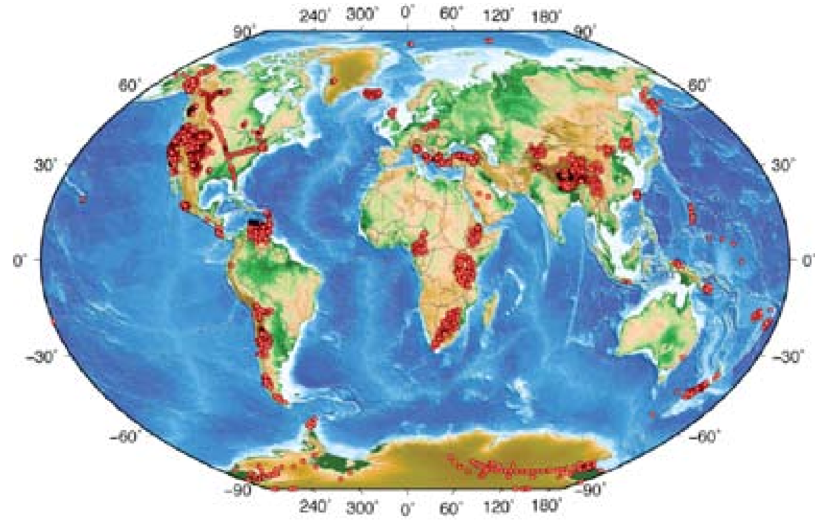
THE INSTRUMENT CENTER

The initial portable IRIS instruments were maintained at the first PASSCAL Instrument Center (PIC) at Lamont-Doherty Earth Observatory, which focused on the broadband sensors used primarily in passive-source experiments. In 1991, a second PASSCAL Instrument Center was established at Stanford University to support a new three-channel instrument that was designed for use in active-source experiments and for rapid deployment for earthquake aftershock studies. In 1998, the instrument centers merged and moved to the current location at the New Mexico Institute of Mining and Technology in Socorro, NM. The consolidation achieved greater technological synergy and coordination within the facility, cost savings from operating a single instrument center, and greater operational space thanks to construction of a new, custom-designed facility, with 7500 sq. ft. of office and lab space and 20,000 sq. ft. of warehouse space. The building was designed by the PASSCAL technical staff and New Mexico Tech to optimize PIC operations, but land and construction funds to build the original facility building and USArray addition were entirely provided by the State of New Mexico through the university.

A major enhancement to U.S. seismological resources and increased activities began in 2003 with the start of EarthScope, including the seismological component, USArray, which is operated by IRIS. Although funded separately, the USArray Array Operations Facility (AOF) and the Transportable Array Coordinating Office (TACO) are both located at the PIC in Socorro. The AOF, which supports the operation of both the Flexible Array and the Transportable Array, shares personnel and logistic support with PASSCAL, leading to significant leveraging and efficiencies for both programs. TACO is staffed and operated as an independent USArray unit that is responsible for the specialized logistic and siting activities required for TA. Again, at State of New Mexico expense, the PIC complex was expanded to accommodate USArray operations, adding 11,000 sq. ft. of office and lab space.

The staff and facility at the PIC provide the equipment, technical support, and training necessary for the seismic research community to conduct field experiments to gather the data necessary to do their research. Approximately 60 new experiments are supported every year, each of which may include training for investigators and students, shipping and other logistical support, field engineers and other technical support during the deployment, and data download and archiving services.

Broadband Stations



Institutions

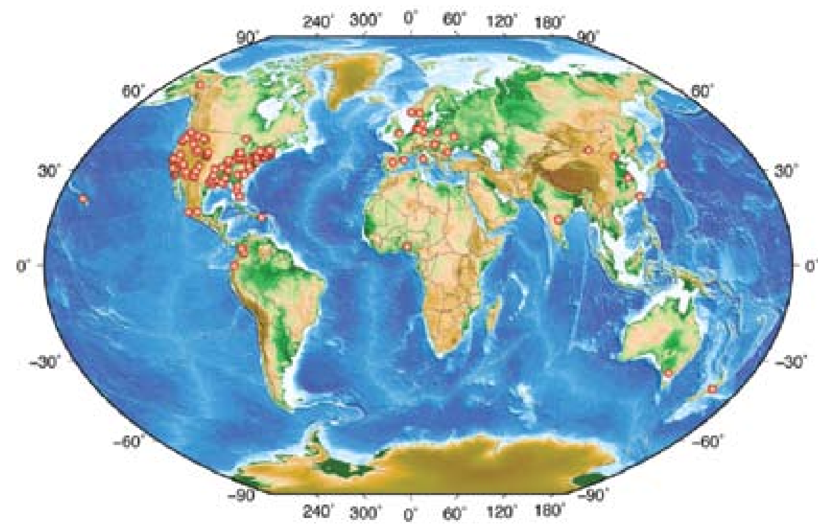


Figure A2.3. (top) Maps of all PASSCAL stations.
(bottom) Map of institutions supported by PASSCAL.

DEVELOPMENTS UNDER THE CURRENT COOPERATIVE AGREEMENT

Thus far during the current Cooperative Agreement, the PIC has supported 302 experiments, an average of 65 experiments each year. Broadband experiments account for one-third of this total, and there have been 75 short-period experiments using passive sources, 51 controlled-source Texan (single-channel) experiments, and 77 high-resolution studies using multichannel cable systems. Of the high-resolution experiments, 33 have been for classroom demonstrations and teaching. The typical number of stations per broadband deployment has steadily increased, with many experiments exceeding 50, and several using more than 75. Although each deployment is motivated by a specific research goal, the combined effect of multiple experiments around the world is to provide a temporary, spatially dense augmentation to the coverage provided by networks, allowing global and regional tomographers to enhance resolution. At the request of this community, one station in each experiment is now designated as "open," meaning that the typical two-year data embargo does not apply.

To ensure that investigators can continue executing a broad range of experiment types efficiently and at the cutting edge, under the current Cooperative Agreement, PASSCAL has continued development in experiment support services in four areas:

- Increased reliability of all equipment used in experiments
- Improved facilities for data archiving support
- Expanded experiment support services
- Specialized support for extreme environments, including polar regions

INCREASED EQUIPMENT RELIABILITY

Equipment for Passive Recording

Instruments now provided for passive experiments include modern data loggers, typically coupled with broadband, intermediate, or short-period sensors. In addition to lower power, these data loggers are proving more reliable, which translates into more uptime and hence more data. They also have better GPS timing, ensuring that the data collected are of better quality than the equipment used through 2004. Most stations are away from commercial power or communications, and rely on solar-power systems and local disks to record data. Advances in electronics and on-site storage have lowered station power requirements to less than 1 W for a passive sensor and less than 2 W for an active sensor installation.

Equipment for Controlled-Source Experiments

The single-channel rapid-deployment REF TEK 125 Texan are used to observe signals from man-made energy sources, such as explosions, airguns, and vibrators. The community draws on a combined pool of nearly 1000 Texans, including 550 maintained at the PIC and others maintained at the University of Texas at El Paso under a Cooperative Agreement with IRIS. There are 1700 additional Texans available in the USArray Flexible Array pool. The Flexible Array pool of Texans introduced a new generation of instruments with greater on-board storage and a modern (USB) communications interface. To unify the PASSCAL and Flexible Array Texan pools and to optimize the combining of the two pools for large, crustal imaging experiments, the PASSCAL Texans were upgraded under the current Cooperative Agreement.

Multichannel equipment has been used very effectively for crustal imaging and a number of shallow studies, including fault zones, aquifers, glaciers, and hazardous waste sites, as well as extensively for training and education in undergraduate classrooms and field labs. These commercial systems are designed for high-resolution seismic reflection and refraction experiments, including geotechnical applications and shallow petroleum exploration. The PASSCAL equipment consists of four 60-channel Geometrics Stratavisor instruments, and ten 24-channel Geometrics Geodes acquired during this Cooperative Agreement. PASSCAL owns three sets of sensor cables for this system: one is used for high-resolution shallow studies; a second, with longer station spacing and lower-frequency geophones, is used in basin and crustal studies; and a third is a snow streamer used on glaciers, ice shelves, ice caps, and sea ice.

Figure A2.4. (left) Completed PIC external sensor vault building. (right) Crane lowering granite slab into place on one of the two piers during construction. *Photos provided by Bruce Beaudoin.*

Telemetry

Recent advances in cell modem technologies simplified telemetry for seismic stations compared to spread-spectrum radios to transmit data to a central data concentrator used in broadband seismic experiments in the past. Leveraging USArray experience, these modem systems have been integrated throughout the instrument pool. For high-latitude and/or remote regions where cellular modems are not an option, PASSCAL has developed a low-power, Iridium modem system for state-of-health (SOH) and command and control. Newer Iridium modems are now being developed that will permit flexible data transmission, up to 10 sps continuously.

Figure A2.5. PASSCAL major equipment. Instrumentation provided and supported by the PASSCAL facility can be divided into four categories: active source, passive source broadband, intermediate and short period, and multichannel.

Station Power

Stand-alone power systems, which are critical in most portable stations and are a frequent point of failure, typically consist of sealed lead acid (SLA) batteries, solar panels, and the associated electronics. Recently, air cells have been successfully deployed where insulation is marginal. For extreme conditions such as low temperatures, where SLAs and air cells lose capacity, use of lithium thionyl chloride batteries have made year-round station operation possible. Charge controllers have been engineered specifically for extreme conditions and are in use in the Antarctic. This new technology is also being used in a new generation power system for the PASSCAL pool of instruments.

Power failures continue to be one of the most common reasons for station failure. Leveraging development from PASSCAL's Polar effort, the PIC designed and is fabricating a new generation of power boxes under the current Cooperative Agreement. These new power boxes, along with the PIC's continuous refinement of field methods, ensure that stations operate continuously throughout deployments and that the data collected are of the highest quality possible.

Equipment Maintenance and Service

PASSCAL initiated development of a new maintenance database during the current Cooperative Agreement. About 15% of the sensors need attention beyond testing between deployments in harsh field conditions. Usually, these repairs are done in house by specialized factory-trained staff. Data loggers returning from the field are also tested, and routine maintenance performed. Board-level repairs are made at the PIC, if required. The new maintenance database is critical for maintaining highly specialized equipment, and provides historical metrics on hardware performance and maintenance efficacy.

Staff Training

The PIC has developed an in-house capability to completely strip and rebuild sensors, which is unique to the community and is based on multiple visits to manufacturers for intensive training. These repairs are paramount to meeting the strong demand from the community to optimize the scheduling of broadband sensors. Turnaround time for repairs from manufacturers can range from months to years, further emphasizing the need for the PIC to provide this service.

Pier Facilities

To satisfy the need for additional pier space associated with USArray and to establish a quieter pier, USArray funding was used to construct an external DC-powered facility with two new piers. Each pier is topped by a 10" thick granodiorite slab installed on lead plugs for coherence across pier positions. In addition to doubling the capacity to test broadband sensors, the new vault has enhanced thermal and airflow stability.

IMPROVED DATA ARCHIVING

Data Archiving Support

A critical part of the archiving process is verification of data volumes prior to shipping to the DMC. PIC refined and expanded the in-house developed, automated system that provides this service. The in-house QC system is designed to catch the most common errors and present the data flow from the PI through the PIC to the DMC in a browseable interface. Prior to, during, and following an experiment, PIC staff members work with the PI to develop correct metadata and

ANATOMY OF A PASSCAL EXPERIMENT

Typical interactions between most PIs and the PASSCAL facility during experiment planning and implementation involve 10 key steps.

Step 1: Planning

Individually or collaboratively, PIs motivated by a scientific question plan an experiment requiring instruments provided by the PASSCAL facility. At this stage, the facility often provides a deployment strategy that will be part of the proposal to a funding agency. It also supplies information for budgets (e.g., shipping costs). An estimate of the equipment schedule can also be provided at this time.

Step 2: Requesting Instruments

The PI places a request for the instruments through the online request form (http://www.passcal.nmt.edu/forms/request.html). Typically, instruments are requested as the proposals are submitted to the funding agency. This step ensures an early spot in the queue once the project is funded.

Step 3: Funding Notification

When the PIs learn that their project will be supported, PASSCAL is notified and the experiment is officially scheduled. In case of schedule conflicts, a priority system exists where NSF and DOE projects share the same high-priority level. Most active-source experiments can be scheduled within a year of funding, whereas broadband deployments have a waiting period of up to 2.5 years.

Step 4: Training and Logistics Meeting at the Facility

Users are required to visit the PASSCAL facility for a briefing on logistics, and training on equipment use. A complete list of all needed equipment and a shipping plan are generated.

Step 5: Shipment Preparation

Equipment IDs are scanned, the equipment packed into rugged cases and, for larger experiments, placed on pallets. The facility helps the PI to generate shipping documents and arrange for shipment. In the case of international experiments, assistance in providing the needed contacts and letters for customs is provided to the investigator.

Step 6: In-Field Training and Huddle Testing

On site, PASSCAL provides additional instrument training for experiment participants. PASSCAL personnel perform a function test "huddle" and attempt to repair any equipment that was damaged during transport.

Step 7: Assisting with Deployment

For active-source experiments, PASSCAL engineers stay with the equipment for the duration of the experiment. They are responsible for all instrument programming and data offloading, with substantial help from experiment participants. For broadband and short-period type experiments, PASSCAL support usually is limited to the huddle test, initial station deployment, and perhaps the first data service run. The goal is to have equipment in good working order and to have fully trained investigators operating the equipment.

Step 8: Service and Maintenance

A typical service cycle for broadband and short-period stations is an interval of about three months. While in the field, if any equipment fails or needs repair, the PASSCAL facility works with the experimenter to supply replacement parts or to perform the repairs as soon as possible.

Step 9: Data-Processing Support

Although it is the PI's responsibility to process the raw data into SEED format, PASSCAL offers extensive support. First, PASSCAL personnel train PIs on the use of programs used for data-quality support and data reduction. Data processed by the PIs are sent to the PASSCAL facility first for verification, are reviewed for completeness of waveforms and metadata, and are forwarded to the DMC for archiving.

Step 10: End of the Experiment

Coordination with PASSCAL at the end of an experiment is essential for a smooth transition to the next experiment. Final shipping documents are generated and PASSCAL personnel track the incoming equipment. Once the equipment is received from the field, it is scanned back into the inventory and routine testing and maintenance is conducted. PASSCAL personnel dedicated to data processing work with the experimenters to ensure that the final data are processed and archived. Any outstanding problems with the data are resolved at the PIC before being archived at the DMC.

to use essential quality-control and processing tools. During passive experiments, staff members receive and verify preliminary SEED data, working closely with the PI to assure data and metadata completeness, accuracy, and quality. Verified SEED datasets from passive experiments are forwarded for archiving as soon as possible, usually soon after they are collected from the field. Active-source data are normally collated and verified following the experiment, and soon after they are archived in HDF5 format.

New Paradigm for Archiving Controlled-Source Data

SEG-Y—the format historically used to archive data from controlled-source experiments—is cumbersome and inefficient. Data in that format require a time-consuming complete rework of a data volume if corrections, additions, and recalibrations need to be made. It is costly to reprocess and re-archive those data. To reduce these inefficiencies, PASSCAL developed an archival processing package—PIC KITCHEN—that organizes data and metadata for an experiment into HDF5 format, decoupling the metadata from the seismic waveforms. Future or last-minute updates, corrections, or additions can thus be folded into small text files, sent, and incorporated with the original data. This process permits data to be archived promptly, ensuring more complete and efficient data archiving. A complementary process extracts raw data and metadata from the HDF5 file and converts them to the format requested by users.

EXPANDED EXPERIMENT SUPPORT SERVICES

The support that PIC provides is essential to the overall success of user experiments. PASSCAL support has evolved through time in response to changing experiment methodologies and technological advances, with a continuing emphasis on improving data return and finding more efficient methods of operation. Support is provided through all phases—before, during, and after an experiment—and is generally grouped into equipment support, logistics support, user training, experiment support, software support, and data archiving support.

Intern Training

Since 2007, PIC and New Mexico Tech have hosted the IRIS Undergraduate Summer Internship Program orientation. NSF REU-supported students from around the United States gain hands-on experience in seismological science, instrumentation, and professional development during this one-week program, then disperse to IRIS institutions for summer research. This program supplements the summer graduate internship that PIC has been hosting, where the intern works with the staff on new developments and assists users and staff in the field.

User Training

To ensure the highest rate of success and to reduce damage to seismic equipment in the field, users are trained on instrument best use and care. With the launch of the new PASSCAL web site, many of the training documents and "How-To's" are now available online. In addition to these electronic documents, PASSCAL produces several trifold field references for users. All PIs visit the PIC for experiment planning sessions and instrument training. Experiment planning sessions ensure that staff are cognizant of project goals and thus can help optimize equipment use.

PASSCAL staff recently organized several training sessions on data handling both at the PIC and aligned with the fall meeting of the American Geophysical Union. Sessions have been well received and attended.

Logistics Support

PIC has created a specialized position of International Logistics Coordinator to handle all import and export arrangements for foreign shipments. The professionalization of this service and availability of a comprehensive facility with specialized shipping documentation have led to a diversified and in-depth understanding of import/export procedures and international transport and insurance requirements. Since this service was established, 100% of foreign PASSCAL experiments have opted to rely on PIC shipping, which is also available for domestic experiments.

Experiment Support

For all experiments, PASSCAL personnel assist PIs to solve technical problems, including repairing instruments on site, troubleshooting problems remotely via telephone and email, and arranging shipments of replacement equipment. In passive-source experiments, PASSCAL personnel typically arrive shortly after the equipment arrives in the field. They are responsible for testing and repairing any equipment that may have been damaged during shipping, and providing in situ training for field personnel. PASSCAL staff members usually participate in some initial station deployments to provide additional PI training. Once this initial support is finished, the PIC will continue to support the PI during the experiment, either on site or remotely, as necessary. PASSCAL staff members normally accompany active-source groups for their entire duration to ensure time-critical instrument deployments, to make repairs on instruments in the field, and to assist in the download of data and organization of metadata.

Software Support

In addition to developing a new method for archiving controlled-source data (see above) the PIC has developed new and improved existing inward- and outward-facing software during the current Cooperative Agreement. Improvements to field software tools have enhanced the user's ability to quickly and efficiently review station status, aiding the evaluation of station performance in the field. A web-based instrument-scheduling database greatly simplifies the complexities of efficiently scheduling 60+ new experiments each year and affords a dynamic schedule to keep the community apprised of instrument availability. These new tools are now part of the larger PASSCAL software suite that consists of programs written over the last two decades by PASSCAL staff and the wider community. The primary functions of PASSCAL software are to assist with collecting data, performing quality control on the data, and transforming data into optimal formats for analysis and archiving. The software is primarily designed to support data loggers provided by the PIC, but has been adopted by many international institutions. There are over 150 fully open-source programs, ranging from simple command line programs, to graphical user interface scripts, to fully graphical data-viewing programs.

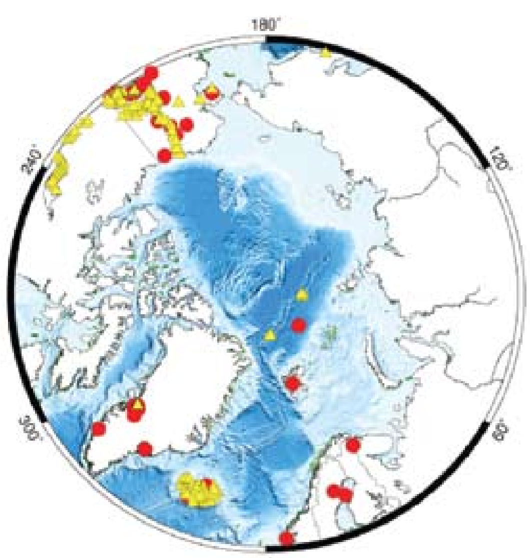
Data Archiving Support

A critical part of the archiving process is verification of data volumes prior to shipping to the DMC. PIC refined and expanded the in-house developed, automated system that provides this service. The in-house QC system is designed to catch the most common errors and present the data flow from the PI through the PIC to the DMC in a browseable interface. Prior to, during, and following experiment, PIC staff members work with the PI to develop correct metadata and to use essential quality-control and processing tools. During passive experiments, staff members receive and verify preliminary SEED data, working closely with the PI to assure data and metadata completeness, accuracy, and quality. Verified SEED datasets from passive experiments are forwarded for archiving as soon as possible, usually soon after they are collected from the field. Active-source data are normally collated and verified following the experiment, and soon after they are archived in HDF5 format.

SPECIALIZED SUPPORT FOR EXTREME ENVIRONMENTS, INCLUDING POLAR REGIONS

In 2006, IRIS and UNAVCO received NSF Major Research Instrumentation (MRI) program funds from the Office of Polar Programs (OPP) to develop power and communications systems that would enable portable seismic and GPS stations to operate in the Antarctic through the austral winter. Based on the results of this work, additional MRI funds were received to construct about 40 broadband seismic stations that could operate for two years without being serviced. These stations are deployed as part of the POLENET (Polar Earth Observing Network) and AGAP (Antarctica's Gamburtsev Province) experiments. Despite being deployed in areas where the ambient temperature reached -80°C, a data return in excess of 90% was achieved.

With these development and acquisition MRI awards, IRIS leveraged PIC expertise to design and develop smaller, lighter, and more robust observatory platforms that have greatly improved science opportunities and data return from the most remote and extreme parts of the Arctic and Antarctic. The activities of IRIS's Polar Services group are described



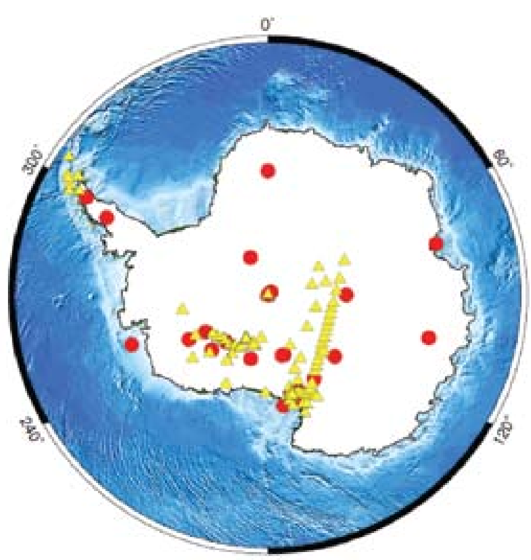


Figure A2.6. Locations of PASSCAL polar experiments.

separately in this proposal, but it is worth noting here that the experience and expertise of PIC staff were essential to the initial effort and, with funding from OPP and additional facilities constructed by New Mexico Tech, the Polar Services group can continue to provide additional needed to support these challenging deployments without taking resources from other projects, without inefficiencies that would arise from a operating an independent facility, and simultaneously introducing new capabilities for operating in extreme environments that can benefit PASSCAL and USArray deployments worldwide.

NEW OPPORTUNITIES AND DIRECTIONS

NEXT GENERATION OF EQUIPMENT FOR EXISTING AND NEW PASSCAL USERS

PASSCAL has benefitted tremendously from advances in technology during its first 25 years. Especially notable examples include advances in storage, GPS timing, and portable broadband seismometers. At present, most PASSCAL systems (some active-source configurations excepted) are highly evolved versions of the original prescient IRIS concept of a stand-alone (occasionally telemetered) data logger attached to a stand-alone sensor. Such systems have anchored outstanding science in deployments of tens to several hundred instruments, and have recently been adapted for polar and other especially challenging environments.

However, scientific results highlighting the remarkable heterogeneity of the deep Earth, and fundamental resolution limits of teleseismic imaging (incorporating wavelengths of several kilometers and longer; 1 s and longer periods), indicate that tighter spacing of recorders and deployments in greater numbers will drive further advances in imaging and understanding processes at the lithosphere and mantle scale. For example, such an experiment in a tectonic region of special interest might consist of a two-dimensional 100 x 100 array of seismographs deployed at a spacing of 5 km. When recording in an aftershock, volcano, glacial, or other microseismicity zone, similar large-array motivations apply to approach unaliased spatial sampling of the seismic wavefield over desirable areas, although the frequencies and station spacing density would be commensurately higher.

Deployment of 10,000 stations using present technology is far beyond current reasonable cost and manpower resource limits. To approach such an experiments requires new deployment strategies and a new generation of miniaturized equipment that can be installed and recovered very quickly, yet that can usefully approach the response, recording, reliability, and other state-of-the-art characteristics of present PASSCAL instrumentation. A key component of such efforts would be a rapidly deployable micro-electro-mechanical systems (MEMS) accelerometer/seismometer-based system that would usefully extend into the body wave band (e.g., to 15 s period) with self-noise approaching the Peterson low-noise curve (e.g., on the order of 1 nano-g/Hz or better out to 10 s). This noise level is approximately 100 times quieter than many currently available microsensors (see Merchant, 2009, available at http://www.iris.edu/hq/instrumentation_meeting/files/pdfs/MEMS_Seismology.pdf), but appears to be approachable with further engineering (e.g., incorporating larger masses than are currently used in such devices and/or averaging over many sensors with statistically independent noise). The handling of data from such large arrays of seismographs will require additional levels of metadata surety and other archive-ready data handling features. Advances in digitizer and GPS hardware should facilitate much smaller digitizer and timing modules, and advances in lithium ion batteries should greatly reduce the size and weight of the power system. Ultimately, a next-generation station should strive to be integrated into a single miniaturized and environmentally secure package that is rapidly deployed in recording mode, and establishes its geographic and instrument metadata upon installation. Such stations, even if not as broadband as current broadband stations, might be very usefully deployed in hybrid arrays, where the vast majority of the stations are intermediate and/or short period, but are embedded in a relatively sparse (e.g., USArray Transportable Array-scale) broadband network that incorporates direct burial, lithium battery, and other efficiency improvements over current installations. Such a hybrid array would thus allow multiscale imaging and otherwise utilize the full range of useful seismic bandwidth. Real-time telemetry for such large networks using current protocols would probably require much lower costs per station than current (e.g., cellular modem) rates. At small scales, self-configuring Wi-Fi network capabilities might make telemetry of even large networks that generate archive-ready data in near-real time technically and financially feasible. Such a telemetered system might also be inexpensive enough to spur novel deployments in especially hazardous environments (e.g., volcano and glacier settings) where 100% recovery of instruments is not possible.

These sensor and electronic technologies and standards are very rapidly evolving and now appear to be at or beyond the requirements necessary for some PASSCAL science (e.g., Flexi-Ramp). Under the newly established Instrumentation Services, IRIS, along with industry, government (e.g., national laboratory), and university partners, plan to proactively pursue the development of miniaturized, low-power systems. This pan-IRIS undertaking hopefully will drive the development of the next generation of seismological equipment for a range of environments. We propose to consolidate this effort with a dedicated engineer to test available equipment, develop complete integrated systems, and interact and motivate PASSCAL-appropriate development within the public and private sectors.

A FLEXIBLE ARRAY FOR RAPID ARRAY MOBILIZATION PROGRAM (FLEXI-RAMP)

Objectives

As the recent earthquakes in Baja, Haiti, and Chile demonstrate, a large earthquake is followed by strong aftershocks, with the largest being one or two magnitude units less than the main shock. If a large network of seismic stations can be installed rapidly in the main shock region, we could capture large events at much greater resolution than has been previously possible with permanent networks. Seismic waves lose spatial coherence after a station separation greater than a wavelength. To capture correlated high-frequency radiation from the largest aftershocks requires much smaller spacing than previously achieved (e.g., <1 km for >3 Hz). FlexiRAMP is intended to provide such a pool for aftershock deployment while also making use of the equipment between big earthquakes.

FlexiRAMP's goal is to install an order-of-magnitude more stations (500–1000) in an aftershock zone for high-resolution measurements. The stations are required to be of sufficiently simple design that they can be installed rapidly and capture the largest aftershocks, the probability of which decays rapidly after the event. Rather than leaving all of the

Table A2.2. Summary of specifications for FlexiRAMP units

Seismometers	Nano g to g at intermediate periods.
DAS	6 channels 24 bit A/D, < 0.5 W, Wireless/GPRS capability, GPS, 200 sps up to 1000 sps, On board data storage for full experiment (GB)
Battery	Lead acid or lithium 10 Amp Hr
Software	Event detect, duty cycle RF, meshed networking, array event detect, real-time warning capability
Design	Single unit with MEMS/wireless/GPS on board and seismometer, solar panel, antenna attached. Plug-and-play components for easy maintenance. Simplicity in installation and networking essential (e.g., throw out of the back of a truck). Lightweight-small form-factor (e.g., Texan size).

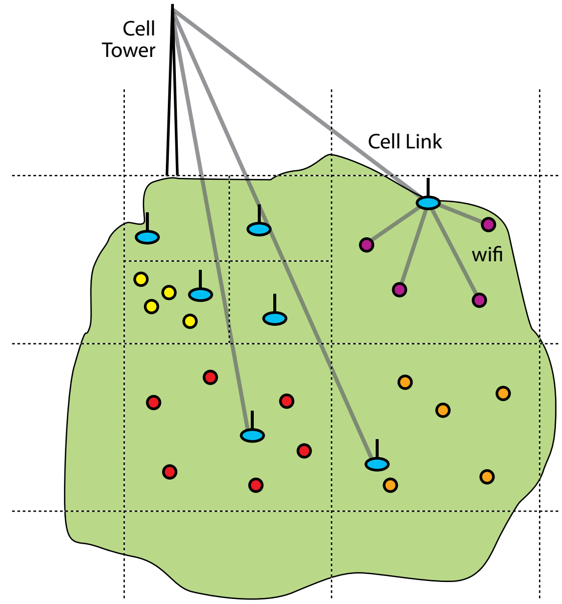


Figure A2.7.

equipment in a warehouse between major earthquake-aftershock sequences, a fraction (perhaps 75%) of the equipment will be used in flexible array mode (i.e., in temporary deployments in earthquake regions). Users could investigate local targets such as magma chambers, structural geology, trapping, scattering and focusing of seismic waves, and harmonic tremor. However, loan of the equipment would be contingent on an agreement to demobilize at the time of a large event and contribute to the RAMP pool. The advantage of this approach is that: (1) expensive equipment is being used for scientific discovery, (2) a pool of qualified operators maintains proficiency with the equipment for rapid deployments after a large event, and (3) more sensors will likely capture a main event while installed elsewhere.

The specifications for FlexiRAMP have been developed at two workshops, one at the IRIS workshop in 2008, and a second sponsored by IRIS at the Seismological Society of America meeting in 2009. We propose a hierarchical array with stations that complement, but do not duplicate, the present broadband pool. Some of the broadband pool should also be installed, as was recently accomplished in Chile. But, for rapid installation, simpler intermediate-period systems are needed with telemetry for rapid event association. It will be necessary to measure both weak and strong motions, requiring sensors with a dynamic range of 10^{-10} g to 2 g, or combinations of strong and weak motion sensors, or emerging technologies. The FlexiRAMP unit should be able to survive on batteries for one week, and on small solar panels indefinitely. It should have wireless and/or cellular communication, technologies that are rapidly advancing.

EXPANDED GEOPHYSICAL INSTRUMENTATION

PASSCAL instrumentation has traditionally been limited to seismometers for recording the wave field, and has not included electromagnetic imaging and seismic sources. However, the purchase and support of small seismic sources and electromagnetic imaging systems would serve and expand the IRIS community in three ways: (1) encourage more shallow seismic work by removing the hurdle of obtaining a seismic source and integrating it with the PASSCAL recording systems, (2) increase the effectiveness of shallow imaging and characterization by providing complementary electromagnetic imaging equipment, and (3) foster ties with the hydrology community, which uses both shallow seismic and electromagnetic imaging systems.

Making seismic sources available to the IRIS community through PASSCAL will provide "one-stop" shopping in which an investigator can borrow a complete seismic system suitable for shallow imaging. This setup will remove one of the main barriers to widespread use of the multichannel seismic recording systems (Geodes), specifically the separate rental and subsequent interfacing of a seismic source with the PASSCAL recording systems. PASSCAL seismic sources would also be a large contribution to the educational use of the PASSCAL equipment, in that it would make it easy for a researcher to image to several hundred meters depth rather than to simply conduct a small-hammer seismic demonstration. The intent is to start with a small purchase—a small weight drop system and radio trigger system—and potentially expand as demand warrants. A weight drop system and radio triggers are being purchased during the final year of the current Cooperative Agreement.

For larger seismic sources, mini-vibrators and full-size vibrators are already available for rental from a variety of government and industry sources. PASSCAL at this point does not intend to commit to purchase or maintenance of these vibrators, but a staff member at the PIC will be charged with keeping abreast of availability and operations of these sources so that PASSCAL can advise the community. PASSCAL also plans to put in place cooperative agreements for mini-vibrators to ease their use within the IRIS community. For explosives sources, IRIS is supporting creation of an Explosives Sources Center as proposed to NSF by the University of Texas and New Mexico Tech.

Moving beyond the modest, initial purchases under the current Cooperative Agreement, a number of items that are beyond the scope of the normal PASSCAL budget and merit additional funding include:

1. Staff time (0.5 FTE) to assist researchers in selecting seismic sources (vibrators, weight drops) for a study, advise on permitting, and helping integrate the seismic sources with the PASSCAL acquisition system. This person would be familiar with available seismic source and with permitting issues (but will NOT carry out the permitting) and, if needed, would be available at the start of active-source seismic experiments that use vibrator sources to advise or be in the field. This person could also negotiate contracts with operators of vibrators to make them more readily available to the IRIS community, and would help maintain and service the additional electromagnetic equipment.
2. The demand for the PASSCAL Geode recording systems is already substantial, and is expected to increase with the availability of PASSCAL seismic sources and the long-term trend of increasing interest in shallow imaging. To maintain the capability of supporting shallow seismic imaging within the research community, the PASSCAL pool of Geode recording systems should be doubled from the current 240 channels to 480 channels. Accommodating these extra Geode channels at the PIC will require an additional 0.5 FTE to deal with maintenance and servicing of more shallow seismic experiments. Additional computers and other miscellaneous equipment will also be needed to support the extra recording channels.
3. To make full 3D imaging of shallow targets possible, PASSCAL soon should bring their total number of Geode recording channels to 1000. Again, these additional recording channels will require more staff time (0.5 FTE), and accessory equipment such as more radio triggers and recording computers.
4. The purchase of ground-penetrating radar (GPR), and conductivity and magnetics instruments, will be useful complements to shallow seismic imaging. In particular, GPR is a method that involves data acquisition and processing similar to shallow seismic imaging, and provides different information about shallow subsurface materials. Conductivity and magnetic mapping permit rapid extrapolation of shallow seismic or GPR surveys in three dimensions. This equipment is widely used in groundwater, glaciology, archeological, and hazard surveys, and will serve to bring scientists in those areas of research into the IRIS community.

The additional Geode channels proposed here reflect the increasing interest in shallow, 3D imaging of contaminant plumes, aquifers, ice sheets, and active faults. The additional capabilities these instruments provide have the potential to increase and improve research in topics important to society, specifically global climate change, water resources, and hazard studies.

INTEGRATED DATA SUPPORT

PIC-supported experiments record data from either passive sources (e.g., earthquakes, ambient noise, and icequakes) or controlled sources (e.g., weight drop, explosion, and vibrator). These data are archived with the IRIS DMC in SEED (passive source) or PH5 (active source) formats. Data from both PASSCAL and EarthScope's USArray Flexible Array experiments comprise over 5 TB of archived data per year. Roughly two-thirds of all data collected with PASSCAL and Flexible Array equipment is from non-EarthScope-funded experiments.

PIC currently provides two levels of data support, one for PASSCAL experiments and one for Earthscope-funded experiments (Figure A2.8). The main difference between these two support levels is that for core PASSCAL experiments, the creation of an archive-ready dataset is the PI's responsibility, whereas for a USArray Flexible Array experiment, PIC staff members create the archive-ready dataset. All archive-ready data are transferred to PIC for QA prior to shipment to the DMC.

The IRIS community has requested the same higher level of support for all experiments that EarthScope-funded experiments currently enjoy. The most compelling arguments for this change are freeing graduate students from the onus of archiving data so that they can focus on research, and improving overall data quality. To effectively integrate data services for both PASSCAL and Earthscope-funded experiments without significantly increasing PIC staff will require minimizing the necessary user support time and reducing manual data handling. In addition to the above advantages, moving data archiving to PASSCAL will provide consistent data services regardless of instrument pool, help remove the ambiguity of what service will be provided when borrowing across pools occurs, and will afford the opportunity to run uniform metrics on all PIC-supported experiment data.

We propose a development effort to streamline data-handling operations so that the same, higher level of support can be provided to all experiments by the time that PASSCAL and EarthScope operations are integrated. For both PASSCAL and EarthScope experiments, the majority of user support time is spent clarifying metadata and instructing users on data manipulation. To minimize this effort, tools need to be developed that will aid the user to consistently capture accurate metadata in the field and that will correctly format raw data recorded on the datalogger to archive-ready data on offload. Both of these efforts are software based and will incur moderate risk. The greatest risks are functional: Can we develop a system that will guide users through the offload process while minimizing user error? Will the increased CPU time required to create archive-ready data be insignificant? And finally, can software mitigate current user support levels?

Localizing all of the data handling from a distributed PI computing network (roughly 40 PASSCAL experiments archiving data each year) to the PIC will require new hardware for computing and data storage. At a minimum, PIC will require a dedicated server for data handling, and a large enough RAID array to store data until they are confirmed as archived at the DMC. We will also require a redundant RAID data storage unit to ensure that no data are lost once loaded on PASSCAL's system. PIC will not maintain a permanent archive of raw or processed data, but will require an on-site backup to ensure efficient recovery if a system fails.

Migrating all EarthScope and PASSCAL experiment data archiving to the PIC will require both new development and maintenance of current and existing systems. We anticipate both field and lab tools will need to be developed and maintained to ensure accurate metadata and to automate tasks that are now done manually by the PI. Maintenance of the current in-house data-delivery system and additions to PIC infrastructure will also require support. An integral part of a new field system will be a dataless generator. This task is nontrivial and will, in part, be contracted to a developer that has successfully integrated a dataless generator in other applications.

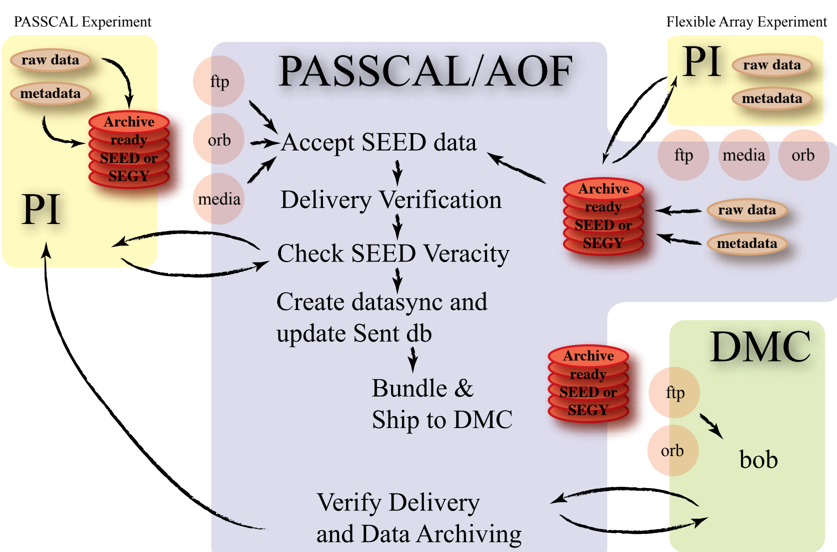


Figure A2.8. Figure showing the difference between PASSCAL and Flexible Array data archiving support. For PASSCAL experiments (left) the PI builds the data archive from the raw data and then ships the archive to the PIC for verification. For Flexible Array experiments (right) the PI is only responsible for providing the PIC with raw data and metadata; the PIC builds the archive.

POLAR AND CRYOSPHERE

Over the past decade, increasing PASSCAL involvement in support of polar research has led to the development of a specialized Polar Support Services group described elsewhere in this proposal. The initial PASSCAL polar efforts focused primarily on support of seismic studies of the crust and lithosphere in Antarctica, but there has been expanded use of PASSCAL resources to support seismic investigations of glaciers and other ice-related processes in both polar regions. Seismic deployments in the study of cryospheric change must cope with the dichotomy of glacial and polar environments: ice and snow are accumulated in high-altitude/latitude, extreme cold conditions, but ice discharge via melting and iceberg calving is focused in extremely wet, unstable marine environments. PASSCAL's approach to coping with these environmental challenges is to adopt a proactive, "get in front of the community" stance in the development of instrumentation, deployment techniques, logistical efficiencies, and data telemetry that address the problems of Earth's icy environments, from the cold, power-starved environments of Antarctica and Greenland, to the challenges of wet, surface-wasting ice-terrains found on mountain glaciers, collapsing ice shelves, and ablating ice sheets.

Specific goals embodied in PASSCAL's support of polar research over the coming period are: (1) assist in the establishment of permanent reference networks in Greenland and Antarctica (particularly focusing on the future legacy of GLISN, POLENET, and AGAP); (2) continue development and support of a "summit to calving margin" sensor deployment capability to support glaciological research in the wet (and corrosive, if atop active volcano) ablating environments of Greenland outlet glaciers and wasting alpine and tidewater glaciers; (3) assess new telemetry technologies for improving bandwidth and power costs in high-latitude and other challenging environments; (4) continue improvement of power systems designed to function reliably and cheaply in extreme cold, wet, or dark environments; and (5) continue support of active seismological experiments designed to establish geophysical parameters necessary for glaciological modeling (e.g., measurements of sub-ice-shelf ocean bathymetry and subglacial lake geometry).

The key outcome expected from the investment of intellectual and material resources in PASSCAL's support of polar, high-altitude/latitude and wet-ablation zone seismology will directly influence the understanding of changing polar environments and, ultimately, global sea level.

3 | DATA MANAGEMENT SYSTEM

HISTORICAL CONTEXT OF CURRENT OPERATIONS

IRIS operates one of the most actively used scientific data centers in the world. The Data Management System (DMS) ingests an exponentially increasing volume of observational time series data every year, from an increasing number of seismic networks and stations. Currently, more than 20 terabytes (TB) of new data are being added annually to the holdings. DMS continues to deliver an increasing amount of data to the research community through batch requests to the archive, streaming data in near-real time, and using advanced application program interfaces (APIs). APIs allow remote clients to access metadata directly in an Oracle Database Management System as well as access the time-series data in mass storage systems. Current projections indicate that the DMS will deliver 80 TB of data to the research community this year. This output-to-input ratio of four attests to the importance of the DMS to the community it serves.

The DMS consists of the Data Management Center based at the University of Washington in Seattle, Washington, and two primary Data Collection Centers (DCCs): the U.S. Geological Survey DCC operated by the Albuquerque Seismological Laboratory (ASL), and the University of California, San Diego, DCC operated by the International Deployment of Accelerometers (IDA) project. The University of Washington receives DMS support for host activities that include data quality assurance and the development of specific applications and algorithms for use at the DMC. IRIS supports additional centers in Central Asia, enabling access to high-quality data sources there. This organization provides a stable pipeline for the flow of data from a variety of sources, though a consistent quality-control process, and into the data archive.

Although it remains challenging to operate the infrastructure and systems that provide access to the thousands of seismic stations, data are now received, archived with backups both on and off site, and distributed via automated mechanisms that work seven days a week, 24 hours a day.

Primary storage for most of the time-series data is a large, disk-based RAID system, but some voluminous, infrequently accessed datasets are still stored on two tape-based robotic systems. The DMC continually improves the software systems that lie at its heart, distributes and supports key software applications used by the global seismological community, and supports and distributes applications that are used by global data centers.

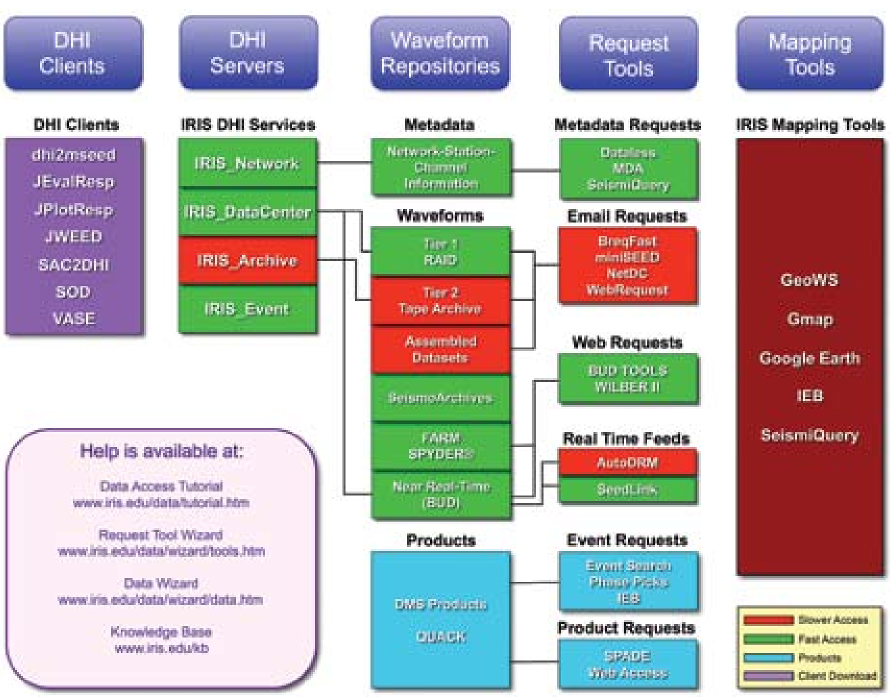


Figure A3.1. Organization of user services and access methods at the DMC.

DATA COLLECTION

Data are received at the DMC through a variety of different paths and protocols depending on the data source.

- *GSN:* ASL and IDA produce data from core GSN stations in SEED format, maintain the metadata describing the seismological observatories, and perform quality control of the waveforms and metadata. DCCs forward the data in real time as well as after completing quality review, usually within a few days.
- *PASSCAL:* PASSCAL experiment data primarily come through the PASSCAL Instrument Center (PIC). Experiment data are sometimes received in near-real time but normally are received with delays of months to years after an investigator releases the data and the PIC completes quality review.

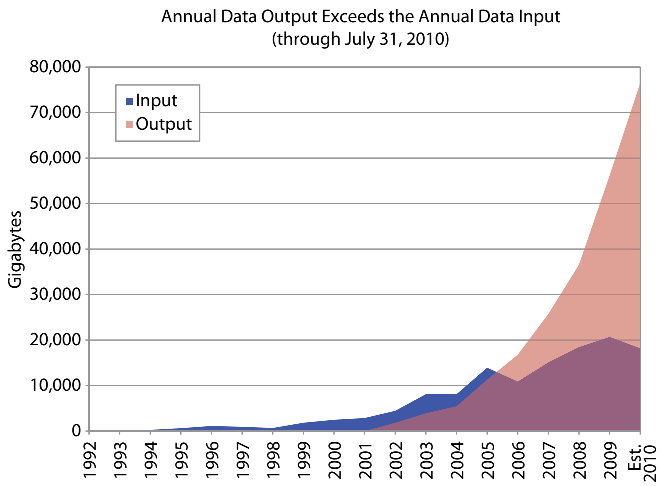


Figure A3.2. The IRIS DMC is an extremely active data center and has become a central component enabling seismologists to do their research. Beginning in 2006, the amount of data flowing out of the DMC exceeded the amount of new data arriving at the DMC, with an estimated 80 terabytes of data being shipped from the DMC in 2010 versus 20 terabytes of new data flowing into the DMC. A ratio of 4:1 is extremely high for a scientific data center and attests to the active use of the IRIS DMC.

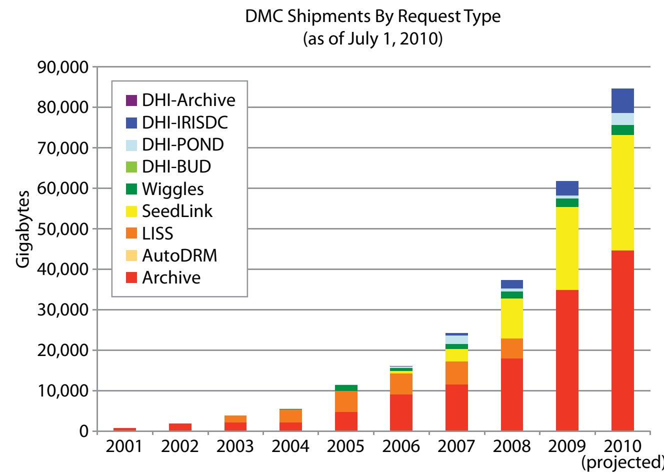


Figure A3.3. This figure shows the amount of data, in gigabytes, flowing out of the DMC by year and by various request mechanisms. We are currently projecting 80 terabytes will be shipped in 2010. The figure shows data shipments from the archive by traditional mechanisms (labeled Archive), real-time feeds (labeled LISS and SeedLink), and by the Data Handling Interface, (labeled as one of four DHI mechanisms). Users of the IRIS DMC use all three primary request mechanisms heavily.

- *USArray:* Transportable Array data are received from the Array Network Facility (ANF) in San Diego. Quality-controlled data from ANF, consisting primarily of data with some gaps to be filled, are received within a few days of real time. Flexible Array experiment data are received from the Array Operations Facility (AOF) in Socorro, New Mexico. Data from the USArray Reference Network are transmitted to the DMC from the USGS National Earthquake Information Center (NEIC) in Golden, Colorado. Three analysts at the DMC review USArray data for quality.
- *U.S. regional networks:* USGS makes data available from all regional networks it supports in the United States, including the U.S. National Seismic Network as well the Advanced National Seismic System. NEIC makes some data available in real time and forwards a quality-controlled version several days later. Most regional networks provide data directly to IRIS and do not make a quality-controlled version available.
- *FDSN:* The International Federation of Digital Seismograph Networks (FDSN) is comprised of approximately 65 different organizations in more than 50 countries. IRIS receives data from the majority of FDSN networks in real time through a variety of protocols. Quality control for FDSN data at the DMC is limited to automated quality assurance processes that are applied to data as they are received in real time.
- *Other networks:* IRIS has bilateral arrangements to collect, manage, and freely redistribute data from many other non-FDSN networks around the globe. Quality control for these data is also limited to automated processes applied at the DMC as they are received.

One of the most significant changes in data reception is that more than 98% of data from **permanent** networks is now received in near-real time. A decade ago, most data were received through non-real-time methods. DMC operates an automated quality-control system that continuously calculates metrics related to data quality for all data received in real time (see http://www.iris.edu/servlet/quackquery). This information is available to any researcher through a variety of web interfaces.

DATA DISTRIBUTION

Originally, IRIS's goal was to service user requests for data given specific lists of seismic stations, recording channels, and time windows. It was expected that a request for data for one earthquake from all GSN stations—about 27 MB of data—could be met within 24 hours, and that there would only be a few such requests daily. Actual services have surpassed this initially daunting requirement by orders of magnitude. In 2009, end users received roughly 60 TB of data, more than two million times more data than for the single benchmark data shipment envisioned in 1987. The number of customized requests in 2009 was more than 600,000—more than 2,000 requests per day.

Data are served through three fundamentally different techniques: responses to formatted email requests such as Breq_fast and NetDC (66%), real-time data feeds (21%), and well-defined interfaces implemented on servers that interact with client applications on individuals' computers (13%). The set of request mechanisms available to researchers is rich and powerful, and targets different types of user requests effectively.

As the number of seismic networks and stations continue to grow, data services continue to be adapted to the needs of users. Gone are the days when users "knew" the names of the stations whose data they sought. Users today are more interested in defining broad regions from which they wish to extract data with characteristics that match their research needs. Most of the significant improvements to data services in the future will be driven by users' needs and employ newly developed tools that let the users get the data they need, sometimes with preprocessing applied. To provide these services, powerful web services are being developed through which users can access data very simply without writing their own applications.

DEVELOPMENTS UNDER THE CURRENT COOPERATIVE AGREEMENT

DMS has always been a leader in the seismological community in developing new tools through which information can be accessed. Additionally, DMS has pioneered methods by which a distributed data center concept can be implemented. An email-based system called NetDC and an Internet-based system called the Data Handling Interface are capable of accessing data from distributed centers seamlessly. Because both of these techniques have limitations, the DMC has been developing modern web services techniques through which a remote client can access time series and the metadata describing them. During the past five years, the DMC has continued developing the tools and systems the scientific community needs for their research, as described below.

DATA COORDINATION

Global

As the FDSN archive for continuous data, the DMC collects data from the FDSN Backbone Network of 200 stations and aims to collect data from one or more stations in every network operating with an FDSN code. The archive currently includes data from 124 of these permanent seismic networks, including 92 networks from which data are received in real time.

Regional

Data sharing is important for seismogenic zones that cross national boundaries, and IRIS focuses resources to improve data exchange in a few critical regions, such as a Central Asia. Representatives from the DMS and the German Research Center for Geosciences (GFZ) met last year with seismologists from Kazakhstan, Kyrgyzstan, Uzbekistan, and Tajikistan, and formed the Central Asia Data Exchange (CADE) group, partly based on GFZ's Central Asia Real-Time Earthquake Monitoring Network (CAREMON) project. The CADE group agreed to readily share data among the Central Asian nations and the outside world via IRIS and GFZ and to work together to seek funding for ongoing network operation within their countries.

DATA HANDLING

Offsite Active Backup

NSF's 2008 management review of IRIS stated that seismological research now relies so heavily upon data services that research would be impaired by a prolonged DMC outage. Prior to this review, all time series, software, and information in the Oracle database were being replicated at an active backup location. Based on the review directive, IRIS began developing the capacity to fully service requests from the remotely located active backup. Although it is now possible to service some user requests from the active backup, development continues. Currently, all routine request processing is still done at the primary DMC in Seattle. In the event of catastrophic failure, however, access to data can be provided from the active backup location.

Enhanced Support for Real-Time Data

One of the primary efficiencies that made it possible to manage exponentially increasing amounts of data and serve an ever-increasing amount of data to the community has been the development of automated systems for real-time data ingestion. Recently, the DMC also developed the capability to distribute data in near-real time using the SeedLink protocol developed by GFZ. Extant SeedLink server systems were incapable of handling the volume of real-time data that users require, so the DMC developed a new system that follows the SeedLink protocol. DMC also developed a "turnkey"

SeedLink server that can be given freely to any network, removing a technical obstacle for networks that wish to share their data in real time.

Production of Merged Data

Often, near-real-time data ("R" data) are received out of order and in duplicate. Additionally, some networks make available a quality-controlled version ("Q" data) of their data within a few weeks after data recording. DMC implemented methods to merge R data with Q data, including complicated steps to remove gaps and overlaps, in response to requests from users.

Seismic Analyst Review

Because of the increased need to manage and assess the quality of USArray data, three PhD-level seismologists now provide expert review of the seismic data from a research perspective. This type of staff support is one of the key reasons why the data quality from the USArray components is so high. With available funding, the capacity to generate automated quality metrics for seismic data can be extended while retaining staff to review the waveforms for quality.

DEVELOPMENTS

Products

A workshop in 2004 (http://www.usarray.org/files/docs/pubs/USArrayProducts.pdf) identified the need to develop a variety of value-added products using data from USArray sources. This concept has been extended beyond EarthScope data to data from many other sources. A vibrant product development activity is now in place (see http://www.iris.edu/dms/products/ for current product availability), and it is clear that this is a priority area for users. Representational State Transfer (REST) web services are the basis for a product management system that allows discovery and delivery of all products meeting specific product type, geographic area, or time constraints. To support this increased effort in products, two product specialists were added to the DMC staff in the past year using EarthScope project funds. These PhD-level staff provide a seismological perspective that is extremely useful in the development of new products as well as an assessment of product generation and quality.

Web Services

DMS has been a leader in the development of new approaches to information dissemination. During the past two years, significant progress has been made in developing a series of REST-style web services that provide access to time-series data, event catalogs, and metadata that describe the events and seismic observatories. The newly developed web services will permit researchers to receive time-series data in a variety of formats, with user-selected processing already applied to the data. A wide variety of processing services are being developed, such as mean removal and down-sampling, filtering, gain correction and unit conversion, instrument response deconvolution, and time-series integration and differentiation. Such services can simplify access to information and encourage use of IRIS data by other communities.

NEW OPPORTUNITIES AND DIRECTIONS

The new tasks the DMS proposes in this 27-month proposal focus on helping the research community address the science identified in the *Seismological Grand Challenges* report. Activities are anticipated in three primary areas:

1. *Continue to ease access to even more seismological data* by providing data curation facilities for networks without existing archival infrastructure, and by acting as a data broker to other seismological data centers with holdings that complement those of the DMC.
2. *Broaden web service development activities to integrate data with groups outside of IRIS.* More complex scientific problems will require simple access to more diverse datasets. While some of these datasets can fit within the IRIS data model very easily, datasets from other domains are best accessed through well-coordinated web services. Web services will allow IRIS data to be more accessible to other communities for their specific uses. Additionally, the IRIS community will be able to more easily access data from other disciplinary data centers that support web services. DMS will develop systems that enable better integrated data access by our internal community as well as those scientists in external fields.
3. *Produce additional products that will aid researchers in pursuit of better understanding of Earth systems.* As the complexity of scientifically interesting research increases, it is clear that the production of higher-level products from which research may begin will assist researchers in studying more complex problems without always having to do routine and mundane data processing.

EASE ACCESS TO MORE SEISMOLOGICAL DATA

Data Brokering Services

In the past, DMS has supported the installation and support for distributed data centers by installing data-access technologies at the specific data centers. While this approach works for some data centers, it does not work in general. For this reason, we propose to develop an FDSN-sanctioned data brokering service. Instead of installing a new data-access technique at a specific center, we will instead provide a service that works with data-request mechanisms already in place and supported by a specific data center. A request will be received by the brokering service, it will be translated into the request method supported at each of the relevant data centers, data will be assembled by the brokering service, and the resulting data volumes meeting the user's specific request will be returned to the requestor. We realize that the full capability cannot be provided at all data centers, but in terms of receiving data in SEED format, the brokering service will very likely provide significant new data to meet a researcher's request.

Value-Added Services for Network Operators

Over the more than two decades of its operation, the DMC has been very successful at opening up data from networks all over the world. To foster even more widespread data sharing, networks with inadequate funding, but a commitment to open data sharing, will be offered a series of value-added services available from the DMC. Of particular interest are the various metrics that DMC computes in its quality-assurance system for all real-time data flowing into the DMC. As an example of their use, managers of the Australian National Network operated by Geosciences Australia have stated that the metrics measured by the DMC QA system are invaluable to them for the operation of their network.

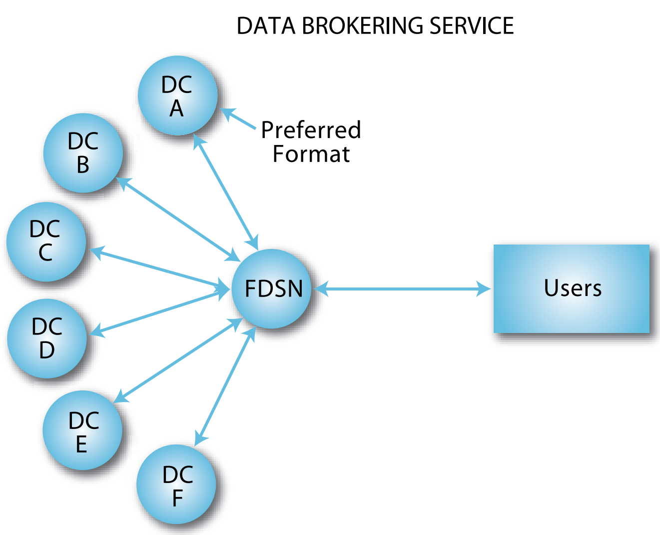


Figure A3.4. This figure depicts how a user of the Data Brokering Service would send a single request to the FDSN brokering service node. The broker would determine which participating data center manages the data being requested. The brokering service would then use the data retrieval mechanism preferred by the specific data center to retrieve the data. This process would be repeated for all data centers holding data requested by the user. The data would then be assembled at the FDSN node into a single product that would be returned to the user, satisfying their request.

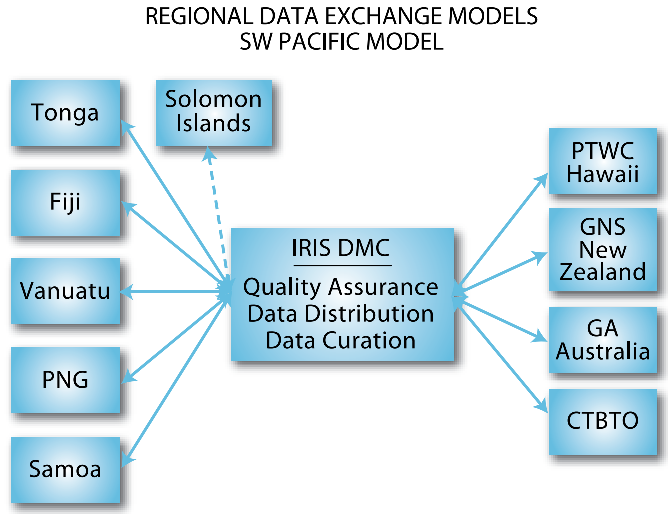


Figure A3.5. The IRIS DMC offers many value added services for network operators contributing data to the IRIS DMC. For instance, as real time data are received, a variety of algorithms are applied to the data that serve as indicators of data quality. A network operator can reference this database of quality estimates as part of monitoring their network performance. Network operators such as members of the SW Pacific Tsunami Task Group, depicted in this figure, are considering sending their data to the IRIS DMC for quality assurance, data archiving, data distribution to other Task Group members, distribution to the international community, and for long term data management. Other international efforts in Central Asia as well as in Africa and the Middle East are also considering this model of data exchange.

Recently a group of countries in the Southwest Pacific met to discuss data sharing in their region. Their decision was to work within the model (Figure A3.5). Data from each of the networks (Samoa, PNG, Vanuatu, Fiji, Tonga, and the Solomon Islands) will send their data to the DMC for quality assurance, data curation, and data distribution, eliminating the need for each country to develop their own systems supporting these capabilities. DMC has developed and has available a turnkey SeedLink server that supports real-time data distribution from a network. Data will be redistributed to neighboring countries through a SeedLink protocol already supported by the DMC. Much of the technical work for this capability is already complete but the promotion of this data-exchange model will require additional effort.

Workflows

DMS develops tools that bring powerful capabilities to the scientific community that are not typically available for purchase. These tools can be linked together in user-defined sequences or workflows. For instance, users will be able to request data, select data based upon waveform attributes (e.g., continuity, signal-to-noise ratio), filter the data, correct for the instrument response, and reformat the data before having the data returned to them for further analysis. While the DMC will produce some workflows that are pre-configured for typical operations, we will also work with Microsoft Research in the use of the Trident Scientific Workflow Engine. A user will be able to interact through a Silverlight-enabled browser with the Trident Workflow Engine to create customized workflows.

WEB SERVICES DEVELOPMENT

Data Access and Processing

DMS proposes to continue development of web services that allow access to waveforms, event catalogs, metadata, and products. This type of access is the current paradigm for information distribution in a platform-independent, scalable manner. We intend to focus our efforts on REST-style web services and coordinate our efforts with our FDSN partners.

We will focus our data-access services on time series in SEED format, event catalogs, and metadata describing the time series and the events. Access to products managed at the DMC will also be enhanced specifically for products in the DMC Product Management System.

We will also develop a series of seismological and generic time series analysis services and expose them as web services. For instance, data rotation, data down sampling, and instrument correction will be offered. In the area of generic time-series services, we anticipate such things as demeaning, tapering, filtering (low pass, high pass, and band pass), correlation, differentiation, integration, convolution, and deconvolution.

We have the existing capacity necessary to maintain the data-access services on computational and storage systems acquired and operated by the DMC. We intend to deploy processing services in a more scalable environment, however, because we cannot independently maintain systems capable of meeting peak computational demands from the external community. First deployments will be on a condominium-style architecture operated at the University of Washington. As developments in cloud services continue, we will be prepared to move to a cloud environment when appropriate.

PRODUCT DEVELOPMENT AND SUPPORT

Project Management System

DMS will continue to support product development through its evolving Product Management System. Staff includes multiple product specialists who take community-vetted ideas and turn them into products, and a developer who focuses on the software infrastructure needed to convert product ideas into actual products.

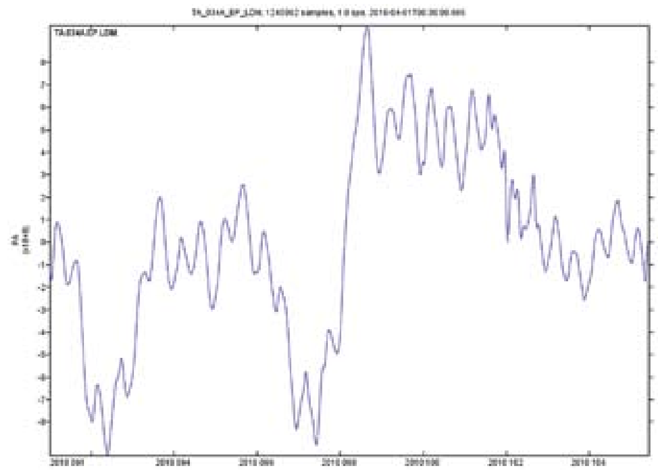


Figure A3.6. Easing Access to IRIS Data for Other Disciplines. The IRIS DMC manages data from approximately 24 different kinds of sensors in addition to seismometers. Traditionally the data have been esoteric and generally understood by seismologists only. This raised a significant impediment for use of IRIS managed data by scientists in other disciplines. The IRIS DMS has embarked on the development of web services that are capable of providing data, with a variety of user controllable preprocessing applied, and with output in very easy to understand ASCII formats. As shown in this figure barometric pressure data as recorded by the EarthScope funded Transportable Array can be provided to an atmospheric scientist in units of pascals, low pass filtered or with other signal processing algorithms applied.

Simplified Data Access for New or Infrequent Users

During the early stages of development of the DMS, the primary responsibility was to serve the needs of research seismologists with extensive experience in data processing and familiarity with the often-obscure details of data formats and instrument response. As access to data has improved and interest in seismology has expanded, services and user interfaces are being developed that respond to the needs of the non-specialist. For instance, a service that allows simple access to corrected time-series data via a URL in a web browser can be a convenient mechanism for displaying waveforms, exploring the archive, and extracting limited amounts of data. The time series displayed in the section in Figure A3.6 shows two weeks of barometric pressure variations in which the raw data have been low-pass filtered and converted into units of pressure. In addition to the screen display, the data can be exported as a series of time-value pairs for convenient input into analysis programs that can accept generic time-series data or even to a spreadsheet program such as Microsoft Excel. This approach is suited to a scientist who wants limited data access, but does not necessarily require all of the details contained in the complex SEED data format. Others may want the data returned directly as a SAC-formatted file rather than having to receive the data, run rdseed, convert it to SAC format, and then manipulate it in SAC. Still others may wish to have the data delivered to an application such as MATLAB. Simplified User Access streamlines access to data by contracting everything into a single step. It eliminates the current approach

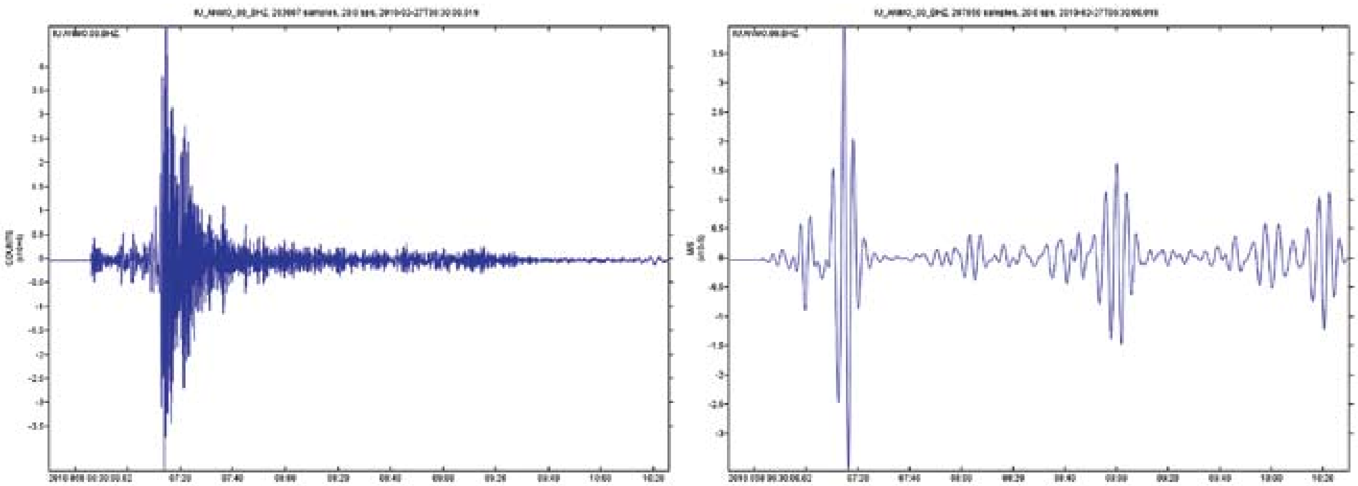


Figure A3.7. The graphic on the left shows the 2010 Chilean earthquake recorded by station ANMO in Albuquerque, NM. The vertical axis is digital counts. The right-hand graphic shows the same information after being corrected for instrument response, and low-pass filtered at 100 sec. The vertical axis is now in units of velocity (meters per second).

of request formulation, request transmission, generation of dataset, retrieval of dataset, conversion of dataset, and ingestion of dataset into the desired analysis tool. DMS will explore the needs of a variety of user communities and significantly expand these efforts to encourage broader use of the increasing variety of data stored at the DMC.

Processed Data Streams

An important attribute of the DMC archive is that primary data are stored with full fidelity, maintaining the complete resolution of the originally recorded time series. No compression or pre-processing is applied that risks degrading the original data. It has been the responsibility of the user to perform instrument corrections, unit conversion, or other processing as part of the scientific analysis. This can be inconvenient or even burdensome for users with limited software tools or processing capability. Tools are being developed to apply a standard suite of algorithms for those who would prefer to have pre-processing performed at the DMC—either for the casual user with limited local resources or the heavy user wishing to pre-process significant quantities of data. For instance, Figure A3.7 (left) shows an earthquake recorded at station ANMO. It is the raw seismogram in units of counts. A preliminary web processing service is in place at the DMC that can correct the data for the instrument gain, and demean and filter. Figure A3.7 (right) shows the same record after it has been low-pass filtered at 0.01 Hz and gain corrected. The units of this waveform are in meters per second after these corrections. A variety of other services are contemplated, including the ability to down sample data from a high sample rate to a lower sample rate. While these added services will be of great utility to a number of user groups, the DMC will always provide the ability to access the raw, unprocessed waveforms for those scientists wishing to more fully control the processing environment.

Request Filtering Using Predetermined Metrics

As the volume of data continues to increase, it becomes more important to provide automated tools and services that allow users to conveniently asses data quality and select those data most appropriate for their research needs. The real-time quality assurance system in place at the DMC calculates many metrics related to data quality as the data enter the DMC. As DMC moves to a web service infrastructure, we can begin adding Quality of Service (QoS) capabilities for data access. During the next 27 months, we plan to begin making progress in this area. We are not proposing to perform dynamic QoS services at this time, but that capability should be considered in the next five-year proposal from IRIS.

Dedicated Processing to Condominium and Cloud Service Models

DMC has historically operated all of its own storage and processing systems using IRIS systems administrators. During the next 27-month proposal, we propose to begin deploying processing web services on the University of Washington HYAK condominium-style computational resource located near the DMC in University of Washington facilities. In essence, a user of the HYAK system buys a specific number of slots providing a specific number of processors, high-speed scratch space, and slower access storage systems, including lower-performance disk and tape systems. The purchase of these slots is good for three years. At the end of that period, a user may choose to purchase an equivalent number of slots for the same price, however, the number of cores and fast storage is likely to have more than doubled in that time and so the same funding will permit access to significantly more computational and storage capacity.

The condominium model also allows access to unused cores in the HYAK system when needed, and similarly, others may use your idle capacity. However, the owner of the slots may always preempt a non-owner when needed. This type of system will allow the DMC to meet peak demand requirements, for instance, after a large earthquake, at a much lower cost than normal.

We envision using HYAK as an initial test of cloud-like services over the period of the 27-month proposal. IRIS would be responsible for deploying services in HYAK but would be relieved of the operation of the system, thus eliminating the need to have IRIS paid systems administrators. DMS plans to provide data services on a modest, multinodal system located close to our primary storage system; however, the processing web services would be deployed in HYAK. These processing services will have a much higher requirement for shear processing power to meet the community's needs, while the data access services are similar to what DMC currently operates and for which DMC has processing capacity to meet current community needs.

4 | EDUCATION AND OUTREACH

HISTORICAL CONTEXT AND CURRENT OPERATIONS

IRIS, with strong NSF encouragement, initiated the Education and Outreach (E&O) program during the 1996–2001 Cooperative Agreement, with the goal of increasing public understanding of Earth science in general and seismology in particular. To set the program in motion, IRIS formed an E&O Standing Committee in 1997. In 1998, the committee convened a conference that included people from diverse science and science education disciplines, funding agencies, and other Earth science E&O programs. Participants were asked to develop a broad vision of how IRIS could uniquely contribute to science education and outreach, and the results formed the basis for a program plan published in 2002. The E&O program has slowly grown from a single IRIS staff member in 1998 to approximately 4.5 IRIS staff members managing a number of subcontract and consultant awards, with significant contributions from members of the IRIS community.

During the past decade, the mission of the E&O program has been refined to focus on advancing awareness and understanding of seismology and geophysics while inspiring careers in Earth sciences. The program draws upon the rich seismological expertise of the IRIS Consortium members and combines it with the educational and outreach expertise of the program staff to create educational and outreach products and activities. Although relatively young when compared to the other IRIS programs, IRIS E&O has already established itself as a model educational initiative among NSF-funded activities and has made significant impacts in a variety of arenas. The guiding principles of IRIS E&O are to deliver programs, products, and services that:

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

In 2009, the E&O program underwent a successful external evaluation by SRI, followed by an external panel review. Until now, the program has closely followed the original 2002 program plan as commended in the 2009 review panel report: *It is impressive how well the program has remained focused upon the objectives identified in this plan.* The program review has provided valuable input into the formulation of a new strategic plan that is the basis for our proposed new initiatives. This new plan includes a refined set of broad goals that underpin the new initiatives. These goals are to:

- *Improve Seismology Education.* Increase the quantity and enhance the quality of seismology education
- *Expand Earth Science Awareness.* Expand opportunities for the public to understand and appreciate seismology
- *Enhance IRIS Visibility.* Increase the visibility and recognition of IRIS through effective branding and communication of IRIS E&O products and services
- *Support IRIS Consortium Members.* Provide education and outreach products and services for members of the IRIS community
- *Expand the Earth Sciences Workforce.* Support development of a larger and more diverse Earth science workforce
- *Strengthen the E&O Program.* Seek collaborations and funding to sustain and grow the E&O program

The original strategic plan included a focus on K–12 and informal education within the E&O program. The new strategic plan maintains successful programs in these areas while emphasizing new development efforts aimed at undergraduate instruction, and workshops and training for the IRIS

Figure A4.1. Refraction/reflection experiment during the intern orientation week at New Mexico Tech.

community. This change in emphasis will also help to serve the needs of early-career seismologists who will be training the next generation.

As the E&O program implements this new strategic plan, the resulting activities and products will be subject to a process of continuous evaluation and improvement via a combination of both internal and external assessments. Results from these assessments will inform the program's decision-making process, allowing IRIS to significantly enhance its E&O activities over time. The SRI external evaluation of the program in 2009 concluded that: *When viewed against the practices of other Earth science and science outreach agencies, IRIS stands out as putting into place the best practices in the field in evaluation.*

DEVELOPMENTS UNDER CURRENT FIVE-YEAR AGREEMENT

SUMMER INTERNSHIPS FOR UNDERGRADUATES IN SEISMOLOGY

Highlights

- 99 undergraduates have participated
- 49 faculty, representing 39 Consortium institutions, have hosted interns
- 85% of alumni have attained or are pursuing a graduate degree in a field of geoscience
- 46% of interns have been female

Since its inception in 1998, the IRIS Undergraduate Internship Program has provided undergraduates with the opportunity to work with leaders in seismological research, to travel to sites around the world for fieldwork, and to produce research products worthy of presentation at large professional conferences. These activities are designed to encourage students, who represent a diverse population, to choose careers in Earth science. Since 2006, this program has been jointly funded through two NSF Research Experience for Undergraduates (REU) site awards as well as through the IRIS core award. REU funding supports student costs, while the IRIS core funding supports infrastructure such as salaries and other oversight costs.

Figure A4.2. Intern orientation field trip, 2009.

To capitalize on its dispersed human resources and research facilities, IRIS has developed a model for a distributed REU site that blends telecommunications technology and recent research on distance learning to achieve the spirit of a traditional REU. The intern experience begins with a one-week orientation designed to introduce the interns to some of the most exciting aspects of modern seismology as well as to foster a strong sense of community among the interns. Visiting scientists from across the IRIS community donate their expertise to lead in-depth laboratory exercises and lectures/discussion sessions. Additional sessions provide training in distance collaboration, an overview of graduate student life, strategies and opportunities to fund graduate education, and insights into industry, academia, and government lab careers.

Following the orientation, interns spend 8 to 12 weeks working on a seismological research project with scientists at an IRIS member institution (Figure A4.2). Each project provides interns with ample opportunities to develop an understanding of scientific inquiry and geophysical data. In addition to regular mentoring by research faculty, an alumni mentor (a student advanced in a PhD program) assists during the orientation week, and also monitors and mentors the interns using the cyberinfrastructure. The IRIS intern program has also developed a set of strategies to enable interns to self-monitor their progress by encouraging them to blog their projects in their own words, identify and structure their goals, monitor and evaluate their progress, and discuss the broader reaches of their work.

The culmination of each student's REU internship experience is the opportunity to present the results of their summer research at the fall meeting of the American Geophysical Union (AGU). Not only does attendance at AGU bring closure to the research project, it is an important opportunity for students to gain meaningful exposure to Earth science research as a viable career option. The longevity of the IRIS internship program allows much of this exposure to occur through networking with numerous internship alumni and potential graduate advisors present at AGU, facilitated via an annual alumni mixer held at the meeting.

Personal encouragement from faculty is an extremely important factor in recruiting interns, and this is especially pronounced for minority applicants. In an effort to increase the diversity of the program, a special lecture series has been developed in collaboration with the North Carolina A&T State Department of Physics to personally invite physics majors at Historically Black Colleges and Universities (HBCUs) to apply to the program. Through this lecture series, dynamic, early-career alumni of the IRIS REU program deliver lectures focused on cutting-edge seismological research with explicit connections to core physics content. The lectures conclude with information on geophysics careers and the role the IRIS Internship Program can play in developing this career path.

PROFESSIONAL DEVELOPMENT FOR TEACHERS AND COLLEGE FACULTY

HIGHLIGHTS

- Over 1150 teachers and college faculty have attended one-day or longer IRIS workshops
- These instructors have the potential to reach over 80,000 students annually
- Tens of thousands of teachers are reached regularly by E&O staff participation on regional and national Earth science and physics listservs

Most middle and high school Earth science teachers have minimal science background in plate tectonics and seismology, and as a result, many of these teachers are poorly equipped to engage their students in geophysics and seismology content or to teach about recent advances in earthquake science and engineering. As a result, many such teachers rely on out-dated textbooks to enhance their own content knowledge and often avoid student inquiry in their instruction.

To support the need for better resources, IRIS E&O and faculty at IRIS member institutions have developed a suite of classroom activities that enable teachers to use seismic data. These data-rich resources provide hands-on and minds-on opportunities for students to explore, for example, Earth's structure, the size of earthquakes, why earthquakes occur, and principles of seismic wave propagation through Earth.

While IRIS-developed resources have been well received by teachers, educational research as well as IRIS formative assessments indicate that training is essential to increase teachers instructional confidence, which in turn allows them to teach in a more inquiry-oriented manner, and deliver more sophisticated content to students. Consequently, IRIS offers a variety of professional development opportunities to supplement its curricular resource effort. These experiences develop deeper content knowledge and understanding, and enhance the use of appropriate curricular materials to enable student learning. These opportunities range from one-hour sessions at regional and national science teacher or informal educator conferences, to multiday workshops offered in partnership with other organizations.

Figure A4.3. Teacher workshop at NC A&T, conducted in collaboration with AfricaArray.

In addition to serving a middle and high school audience, IRIS has recently begun to employ a similar approach to undergraduate instruction at community colleges and small liberal arts colleges, where faculty generally have a strong geoscience background, but rarely with a focus on seismology or geophysics (Figure A4.3). IRIS's involvement at venues such as the National Association of Geoscience Teachers, the Geological Society of America, and the Cutting Edge Workshop series have been highly successful and are an opportunity for IRIS E&O to further enhance geoscience instruction.

PUBLIC DISPLAYS FOR MUSEUMS AND OTHER VENUES

HIGHLIGHTS

Specialized Displays

- Annually, 13 million people visit the three museums where there are major IRIS/USGS displays
- 1.7 million people per year visit the Franklin Institute where a new IRIS E&O display was installed in 2010

Active Earth Display

- Over 105 groups have applied for accounts, 61 of which are schools, colleges, or community colleges, and this number is rapidly increasing
- 37 displays were in operation in June 2010
- Users estimate over 75,000 people per year will visit the existing displays

Museums are an important mechanism for scientific outreach to the general public, and the display of real-time seismic data offers the opportunity to capitalize on visitors' enthusiasm for current information. Thus, IRIS works with individual museums to help them create custom displays as well as to explore new opportunities such as the projection of near-real-time seismicity on three-dimensional globes. As an outgrowth of our experience creating large museum displays, including surveys of audience response (Smith et al., 2006, *Eos*, 87(8):85), IRIS has developed a more-versatile, and less-costly Active Earth Display that is aimed at smaller formal and informal learning institutions. These displays have been installed in locations ranging from visitor centers in national parks to small museums, NSF headquarters, departmental lobbies in universities, and at South Pole Station.

Although the content is delivered via a web browser, the system has many features that distinguish it from a simple web site. The Active Earth Display content pages are designed for interactive use with a touch screen, but the display can also be cycled in a non-interactive mode. The availability of content pages can be individually tailored for each site by the end user. Placeholder pages can be used to permit insertion of new material, such as teachable moment pages after significant earthquakes. Packages of content pages, such as the seismic and tectonic settings of Cascadia and the Basin and Range have been developed in collaboration with UNAVCO and the EarthScope National Office, and there are now more than 65 pages of content to choose from.

Figure A4.4. Active Earth Display kiosk and sample screens.

SEISMOGRAPHS IN SCHOOLS

HIGHLIGHTS

- Over 170 schools are currently operating seismographs provided by IRIS
- Over 375 users of educational seismographs from 42 states and 16 countries have registered their station in the Seismographs in Schools database
- Over 58 of these stations have displayed real-time views of their data on the web.
- Since 2004, 140 teachers have attended an AS1 users training workshop.

One of the best ways to engage students in scientific content is to give them opportunities to work with real scientific instruments and data and enable them to experience the discovery of scientific information. The Seismographs in Schools program is now doing this for thousands of students in physics and Earth science classes around the country. The foundational activity has been the dissemination of educational seismographs (the AS1) and software to classroom teachers and the development of a training workshop and curricular materials for teachers. More recently, a cyberinfrastructure has been developed to network teachers, both within the United States and internationally, to enable them to assist each other with technical issues as well as extending the value of the program by encouraging conversation on scientific content and instructional approaches. The seismometer also becomes a community resource, as local media commonly feature the school and their seismograph after a major earthquake (Figure A4.5).

However, the SIS program is based on more than the placement and support of AS1 seismographs in schools, as IRIS E&O has a pyramid goal of engagement:

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

Figure A4.5. Example of local TV news coverage of school seismographs.

Figure A4.6. AS1 training workshop for teachers.

As part of this strategy, IRIS encourages, collaborates, and supports both national and international educational seismology networks. For example, within the United States there are groups in over nine states that provide regional support for teachers. Internationally, IRIS has provided seed equipment and shared expertise with school seismograph networks at various stages of development in countries such as New Zealand, Great Britain, Ireland, France, Italy, Kazakhstan and Costa Rica. This work includes the development of an online database system that allows other educational networks (e.g., Great Britain) to share their data with schools using our site.

TEACHABLE MOMENT SLIDE SETS

HIGHLIGHTS

- Rapid creation of slide sets after 7 major earthquakes in the first 7 months production
- 100,000 visits to the Teachable Moments web page during February-March 2010

A major new addition to the set of IRIS E&O products in the past year is the production of Teachable Moment (TM) presentations following major earthquakes. Newsworthy earthquakes can capture the attention and imagination of students, however, many instructors lack the time and/or background knowledge to synthesize available web materials into a coherent package that tells an educational story. By delivering timely, easy-to-use resources, the TM presentations enhance Earth science education by expanding classroom discussion of seismology concepts and tectonic processes.

TM presentations, produced in collaboration with the University of Portland, are generally posted to the IRIS web site within 24 hours of the event. Each presentation is formatted in a way that allows an educator to tailor the materials to their particular audience and time frame. Common elements include USGS earthquake and volcano information, plate tectonic and regional tectonic maps and summaries, custom-generated computer animations, seismograms, AP photos, speaker notes, and other event-specific information, some of which is contributed by IRIS Consortium members. Full TM presentations were created for seven earthquakes from October 2009 through April 2010, and shorter TM presentations were made for seven less-newsworthy earthquakes in the same time period. The Haiti and Chile earthquakes were by far the most significant in terms of visibility, and in both cases, additional information, animations, lesson plans, activities, and other educational materials were added to the site.

Revisions to the IRIS web site have enhanced the visibility of and the traffic to the TM page. In addition to being prominently featured on the home page of the IRIS web site, notification of new TM presentations are distributed via a mailing list, on the IRIS E&O Facebook page, and on two Twitter accounts (one in English and one in Spanish). The custom animations that accompany the presentations are posted to YouTube to reach an even wider audience, resulting in nearly 25,000 views from January–May 2010. Perhaps even more important is the viral nature of the TM announcements as these are frequently reposted to teacher listservs, reposted on Facebook, and retweeted.

To expand the impact of the Teachable Moments, a number of improvements are proposed. More seismogram interpretation and fault mechanism information will be added that could be used in undergraduate classes, and TMs will be tied more closely to new automated DMS data products such as the Ground Motion Visualizations. An Active Earth Display page will be created for each event, which will automatically appear on displays that subscribe to TMs. As done for the Haiti and Chile earthquakes, additional educational products will be provided along with Microsoft PowerPoint sets. Options are being explored with the USGS to make more use of their automated event information system. Such collaboration would combine the USGS's scientific and public information expertise with IRIS E&O's educational experience.

WEB RESOURCES AND ANIMATIONS

HIGHLIGHTS

- In the first five months of 2010 there were over 2,500,000 visitors to the IRIS web site with the majority viewing the Seismic Monitor
- Over 80 animations on seismology topics are available in the animation library

The IRIS web site is the face of the Consortium to the general public. A key way to increase the impact of the E&O program is to drive more traffic to the web site and provide content that

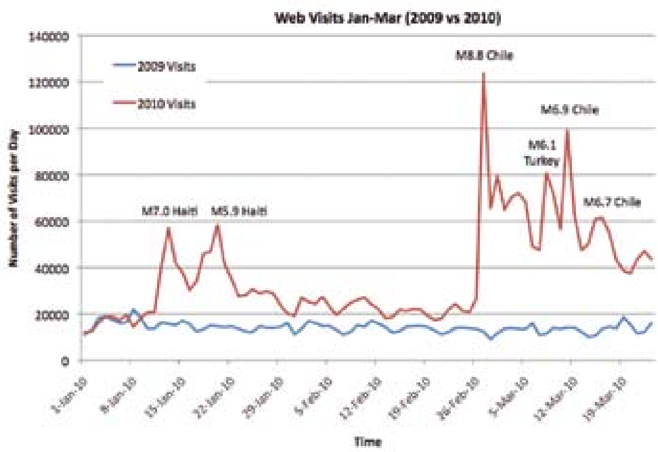


Figure A4.7. Daily web page visits, Jan-Mar, 2010.

brings users back to the site. Content includes timely information about recent seismological events as well as longer-lasting information such as classroom activities and animations.

Figure A4.7 shows the value of recent changes to the web site, where the increase in traffic after an earthquake results in both a short-term peak, and a long-term increase in users. This long-term upswing in users has been achieved by examining all of the delivery venues for educational content, followed by revisions and reorganizations across the web site, increased use of social networking sites, addition of new educational resources, and encouraging other groups to link to our materials.

Earth science teachers with limited geologic knowledge, as well as seasoned professors, are eager to supplement existing teaching resources with computer animations of geologic processes. Unfamiliar scientific concepts can be more accessible when learning is supported by animations, and the dynamic nature of animations may better engage the current generation of students. IRIS E&O offers cartoon and interactive Flash animations covering a variety of seismology and Earth science topics. Accompanying video lectures both promote Earth-science teachers' grasp of new science content and support their classroom presentation of earthquake science. To complement these, most of the animation and video lecture sets also have links to classroom activities that promote active learning of key seismological topics.

Another example of the increased use of the IRIS web pages is the IRIS Image Gallery, a diverse collection of photographs and visuals that encompass the range and breadth of seismology and the seismological community. It includes educational images from E&O posters, and research figures submitted by the IRIS community, as well as photographs of IRIS community activities worldwide, from workshops to field deployments.

Figure A4.8. Sample online resources.

IRIS/SSA LECTURESHIP

HIGHLIGHTS

- 17 IRIS/SSA Distinguished Lecturers have given over 99 presentations to public audiences of up to 400 people per lecture at major museums and universities throughout the country
- Average attendance is 165 per venue
- All venues surveyed in 2009 described the lecture as a success and 100% were interested in having a lecturer for the coming season

There is a strong demand at informal learning institutions like science museums to provide local communities with direct contact with distinguished scientists. In 2003, IRIS and the Seismological Society of America (SSA) initiated the IRIS/SSA Distinguished Lecture Series to help meet this need. Two or three speakers are selected each year for the lectureship from a pool of nominees generated from the IRIS community. Selections are based on scientists' ability to convey both the excitement and the complexities of seismology to a general audience in a form that is engaging and enlightening. These lectures reach a broad sector of the public with an interest in science through venues that often have a well-established lecture series.

To address the requests from educators for electronic versions of these lectures so that they may incorporate the information into their own classroom lectures, lecturers are asked to ensure that their presentations are suitable for distribution via the web or CD-ROM, and videos of some lectures are placed online. The impact of the lectureship program is also increased by having many venues arrange additional events in conjunction with the lectures, such as webcasts, radio interviews, teacher workshops, and IMAX films. In addition, the speakers frequently give a separate technical talk on their research at local university geoscience departments.

PUBLICATIONS AND GENERAL OUTREACH

HIGHLIGHTS

- Five educational posters and seven "one-pagers" have been developed
- Over 100,000 IRIS educational posters have been distributed to schools, colleges, and universities, including institutions in 22 different countries
- Several of the posters and all of the one-pagers are available in Spanish

IRIS produced its first educational poster (Exploring the Earth Using Seismology) in 1998 and continues to give out thousands of copies of that poster each year. IRIS has continued to develop new posters since then, on topics such as the 2004 Sumatra earthquake and the commemoration of the 1906 San Francisco earthquake (Century of Great Earthquakes). Recent posters have been aimed at high school and college students, and the full range of posters can be found at schools and universities throughout the world. To maximize the effectiveness of future posters, research was recently concluded on the use of posters in classrooms. The intention of this project was to identify a set of design features that increased their instructional usefulness, and new posters are being designed based on those results (e.g., Figure A4.9).

While IRIS E&O will continue to supply paper materials because of the important role they play in education and outreach venues, particularly school classrooms, the program is moving toward greater electronic distribution of materials such as videos, animations, and podcasts. Materials are now also distributed via DVD, as with IRIS's "Earthquakes" DVD, developed in collaboration with EarthScope. This DVD is an organized collection of electronic earthquake education resources, including both IRIS material (text, images, video, and animations) and high-quality activities from other sources.

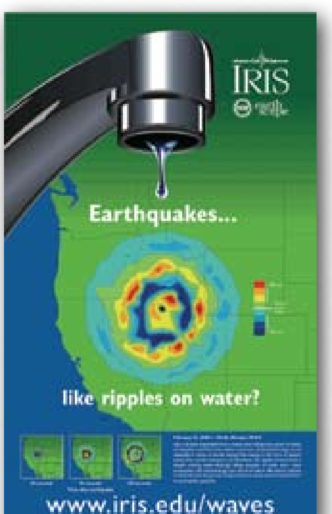


Figure A4.9. New poster highlighting Transportable Array data.

ENGAGEMENT OF DIVERSE AUDIENCES

An IRIS E&O priority is reaching and enfranchising a diversity of audiences with all of our activities, using three complementary approaches: (1) establishing and strengthening partnerships with programs and organizations specifically designed to serve underrepresented groups, (2) expanding individual IRIS E&O activities to engage these same groups, and (3) targeting underrepresented groups to include them in greater numbers in existing activities.

A successful approach is to build partnerships with groups that are already engaged in successful activities. An example is partnering with the Society for Advancement of Chicanos and Native Americans in Science (SACNAS). SACNAS has increased its emphasis on Earth science in the past several years through the efforts of Aaron Velasco, a former IRIS E&O Standing Committee member, and past president of SACNAS. IRIS has shared a booth at the SACNAS annual meeting for the past four years as well as cosponsoring an Earth sciences field trip at the meeting.

Interactions with SACNAS complement IRIS E&O's collaboration in UNAVCO's RESESS program (Research Experience in Solid Earth Science for Students), which provides a supportive summer research environment for underrepresented minorities. RESESS allows students to transition from research within a small student community to involvement with scientists throughout the United States. IRIS has shared student applications and research mentors between the programs so that the best match is found for students and hosts, and IRIS is now a co-PI with UNAVCO on the recently awarded five-year Opportunities for Enhancing Diversity in the Geosciences grant that supports the RESESS program. Through this collaboration, IRIS will be working intensively to increase opportunities for minority participation in IRIS activities as well as integrating the RESESS program into other opportunities that IRIS offers students.

E&O program staff members are also working with Penn State University and North Carolina A&T (an HBCU) on the AfricaArray project. This project is designed to increase educational capacity in Africa and increase the engagement of African American students in Earth science. As part of that process, IRIS E&O provides multiday professional development to teachers in North Carolina working in the highly diverse Greensboro region.

Wherever possible, underrepresented groups are targeted in existing programs. Diné College, a Native American college, was one of the first IRIS Educational Affiliate members, and

HBCUs will be approached as potential Educational Affiliate members. The USArray siting outreach program has made special efforts to engage minority groups, such as the multi-year project with Navajo Nation associated with the deployment of USArray stations in Arizona. Minority-serving institutions are targeted in advertisements for hosting a Distinguished Lecturer as are schools with a large percentage of students from underrepresented groups when selecting schools for AS1 seismographs. As part of the increased emphasis on use of online resources, the Spanish translations of web materials will be increased. The Spanish Teachable Moment presentations have been very popular, particularly after the 2010 Chile earthquake, and greater use is expected as part of IRIS's international development activities in Central and South America.

INTEGRATION WITH USARRAY

Considerable integration has already occurred between E&O and USArray Siting Outreach. All E&O products are already available for use by USArray, and USArray products are used and promoted by IRIS E&O. This integration will increase even further within the new IRIS management structure. Other examples include:

- Selection of new AS1 schools is focused on current or near future Transportable Array footprint
- Active Earth Display can be used to highlight USArray activities
- Professional development for either program depends on exercises and/or data from the other program
- Production of a new poster

NEW OPPORTUNITIES AND DIRECTIONS

Engaging undergraduates in real data analysis and providing them with current research examples can greatly improve their appreciation of science and increase the likelihood that they will continue on to a scientific career. To pursue this goal, a key E&O program focus during the next 27 months will be to develop new materials and programs for undergraduate education. This focus will allow IRIS to leverage the talent and resources that are available within the Consortium membership, and to make those resources available to a wider audience. The need to reach a wider audience is even more pronounced in the current environment where over 40% of undergraduates attend community colleges (see American Association of Community Colleges Fact Sheet at http://www.aacc.nche.edu/AboutCC/Documents/factsheet2010.pdf). Historically, the E&O program has emphasized middle school and high school audiences because of the great need for resources at those levels and the importance of capturing the imagination of students before they lose interest in science. However, the IRIS E&O program is mindful of the strengths and foundations of its program and the responsibility to serve the IRIS community. Here, IRIS E&O has the opportunity to use its university linkages to engage an extensive educational community, including expanding IRIS Educational Affiliates membership, to impact future practitioners in both research and education.

The other major focus during the next 27 months will be to greatly expand the impact of existing activities and resources. For example, to reach larger audiences for professional development, and accommodate the limited time of instructors, will require developing more short video segments and podcasts to deliver online training in support of pre-existing classroom activities, and fewer in-person workshops. It will be important to evaluate and, if appropriate, adapt efficiently to new methods of information dissemination as they continue to become available, whether it be mobile devices or new social networking sites. IRIS E&O is also aware of the need to reach a diversity of audiences, and is constantly working to find additional mechanisms for reaching minority and international audiences. The following sections outline new and modified E&O activities that are proposed over the next 27 months.

CREATE AND CURATE UNDERGRADUATE SEISMOLOGY RESOURCES

An important initiative by IRIS E&O to place more emphasis on undergraduate education will be to create, collect, and curate classroom and lab exercises that can be used throughout undergraduate geoscience curricula. There is a great need for these materials as recent scholarship has shown that undergraduates hold significant misconceptions about earthquakes and plate tectonics despite instruction using existing resources, and only 5% of undergraduate respondents recognized that scientists knew about Earth's layers based on information from earthquakes (Delaughter et al., 1998, *Eos*, 79(36):429–436; Libarkin et al., 2005, *Journal of Geoscience Education*, 52:17–26).

Instructors compiling their own set of classroom exercises often use activities posted on science teaching web sites such as the SERC (Science Education Resource Center at Carleton

College), DLESE (Digital Library for Earth System Education), USGS, SCEC (Southern California Earthquake Center), and IRIS. On the SERC web site, over 50 seismology-related activities are available, including those submitted by participants of the 2007 "Teaching Geophysics in the 21st Century" workshop in which IRIS staff participated and IRIS community members helped organize. Over three-fourths of these activities, however, are designed for upper-division students in advanced geophysics courses. Although the workshop helped increase the number of available geophysics activities, it also highlighted the great need for high-quality activities that use current data for introductory and intermediate-level geoscience courses. IRIS E&O will concentrate development efforts on materials that address these audiences.

Though the questions in the *Seismological Grand Challenges in Understanding Earth's Dynamic Systems* have been posed to help guide fundamental seismological and geophysical research for the next several decades, they also offer fresh content for developing new resources for the college classroom. Most of the 10 Grand Challenges address how seismology illuminates our understanding of Earth structure and address issues related to plate tectonics and related phenomena such as convection and volcanism. A few of the questions naturally allow for the use of active-source seismology in a classroom exercise, a topic that is largely absent from introductory classes despite its connection to societal issues. Furthermore, each of these questions represents course content that is already being covered in lower-division physical geology courses and aligns well with the newly developed *Earth Science Literacy Principles* (http://www.earthscienceliteracy.org).

Perhaps the greatest strength of using the 10 Grand Challenges as the content guide for course materials is that it permits integration of cutting-edge research into the classroom while allowing instructors to cover the same core content. Additionally, using the Grand Challenges as the content guide will extend the reach of the document to many undergraduate faculty who might otherwise be unaware of these important research questions.

The creation of new classroom materials has begun under a recently funded CCLI grant in collaboration with the College of New Jersey (TCNJ). The objectives of that project are to:

- Create undergraduate instructional materials and a detailed instructor's guide that correspond to each of the Grand Challenges, as well as at least six inquiry-based laboratory activities
- Disseminate developed resources through the IRIS web site and digital libraries such as SERC and DLESE, via workshops for undergraduate instructors, and through special sessions at national geoscience and seismological meetings

Achieving these objectives will provide first steps toward increasing the level of inquiry in seismology-related instruction in introductory geoscience courses and in courses such as structural geology and tectonics. As initial materials are developed, seismology faculty will be invited to share their rough exercises via a "faculty only" area on the IRIS web site (as requested by an IRIS early career faculty group). IRIS will assist in editing the submitted materials to make them more easily usable by other faculty. IRIS E&O will also conduct workshops with undergraduate faculty to vet, improve, and disseminate these new materials.

INVOLVE MORE UNDERGRADUATES IN FIELD RESEARCH

Each summer, numerous efforts to collect seismological data are underway within the IRIS community and most such experiments have a need for field assistants. As a result, the IRIS community has asked the IRIS E&O program to leverage the existing internship program infrastructure to develop a clearinghouse for recruiting undergraduate field assistants. This clearinghouse will also provide opportunities for students not currently part of the IRIS community, including math or physics students who might have an interest in seismology but have never taken a course or participated in fieldwork before, foreign students who are not eligible for REU programs, or community college students who might not yet have the prerequisites for an IRIS internship.

While this partnership with community members will provide needed students, it will also allow IRIS E&O to ensure that the field assistantship is more than just manual labor. The PI application process will be structured to ensure that PIs provide related learning experiences for the field assistants, rather than just handing them a shovel. Activities might include providing reading lists that will help the intern under-

Figure A4.10. Students installing seismographs as part of the Sierra Nevada Earthscope Project.

stand the scientific context for their fieldwork, pre- or post-fieldwork seminars on local and regional tectonics, and/or sessions providing instruction on data processing techniques.

Under this initiative, the robustness of the application and review system will be improved. Students seeking field assistantships will be able to enter and update their information online and provide details about available dates, potential locations, and topics of interest. The system will generate email notifications for projects that match their criteria. Similarly, when a PI lists a field opportunity, they will define their project according to parameters that will help ensure a good match between projects and students.

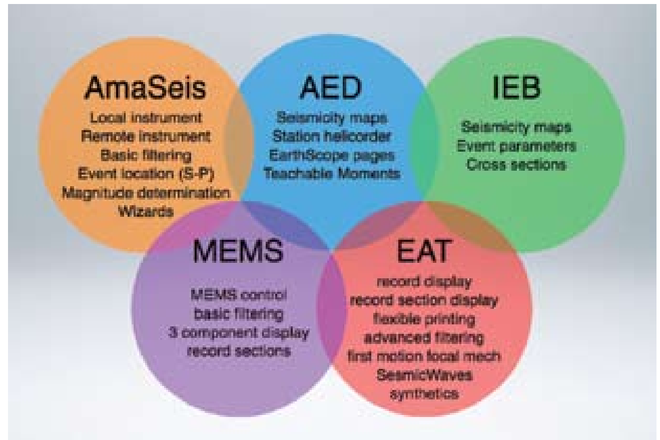


Figure A4.11. Software vision.

NEW DATA ACCESS AND ANALYSIS SOFTWARE

Software Strategy

A coherent set of software applications supporting IRIS E&O goals in seismological education and the E&O pyramid plan of engagement will be delivered. Most of these applications already exist and will be improved while one is an entirely new product. These applications will have the following properties:

- A well-defined scope (i.e., it will be easy to describe to users what a particular application does or to point users to the appropriate application for their needs)
- Contain a wide enough set of features so that most educational activities require using only one application, which implies some overlap in functionality but not so much as to obfuscate differences in the applications

The applications support the increased emphasis on the undergraduate audience, and all will be of use in the undergraduate classroom.

Figure A4.11 shows the software vision. The applications are:

- *Amaseis.* The primary function of Amaseis is to view and locally store data from seismographs such as the AS1 currently used in the Seismographs in Schools program. Enhancements to Amaseis will allow the data to be shared in near- real time among classrooms within a school or schools within a school district. Amaseis will also contain the analysis tools needed for K–12 exercises, including epicentral location and magnitude determination. The current overhaul of Amaseis has the following goals:
  - Rewrite in Java for a maintainable and platform independent code base
  - Add the ability to share data in real time via IP port 80 to avoid firewall issues
  - Display near-real-time data feeds from the DMS
  - Include help and prompting features to lower the use barrier for teachers
- *IRIS Earthquake Browser.* The primary function of IEB, developed by the IRIS DMS, is to allow users to explore seismicity data via a Google map-based interface. Although not initially developed for an educational audience, the ease of use and intuitive interface lends itself to exploration by the educational community and the general public. Results of customized searches are displayed on the map for analysis, but can also be downloaded in a variety of formats for analysis. We propose to add three-dimensional viewing capability to the tool to allow even more exploration.
- *Active Earth Display.* The primary function of Active Earth Display is to deliver interactive seismological and tectonic content to both formal and informal learning settings. The Active Earth Display will evolve into a more flexible delivery platform as described below.
- *QCN/MEMS.* The software developed in collaboration with the Quake Catcher Network (described below) will support the use of micro-electro-mechanical system (MEMS) accelerometers in classroom activities. This application will support the display, recording, and storage of single and multiple component waveform data, simple filtering, and perhaps the ability to record and display record sections from daisy-chained MEMS accelerometers.
- *Event Analysis Tool.* This new application will be aimed primarily at undergraduate instruction. The goal is to allow easy use of DMS datasets in classroom and lab exercises. The application will include the ability to display multi-component waveform data, plot record sections, filter and window data, convert waveform data to multiple formats, display and manipulate focal mechanism data, perform magnitude calculations, generate synthetic seismograms, and display seismic wave propagation paths. This application will leverage the new web services developed by the DMS.

EXPAND ACTIVE EARTH DISPLAY USAGE

The Active Earth Display, as described previously, is poised to become a vehicle for the delivery of IRIS educational materials on a much larger scale, including enabling this system to be deployed in K–12 classrooms and schools, undergraduate geoscience departments, and local museums and parks. To achieve this much larger scale of deployment, we propose to make several improvements and modifications to the Active Earth Display system and then to greatly increase the marketing of the displays. Although the model has been to primarily provide the content of the display with each venue providing their own hardware, the hardware costs can sometimes be a barrier. Thus, partnership with hardware manufacturers will be pursued to support this effort through donated or subsidized hardware.

Adapt the System to Arbitrary-Resolution Displays

Integrated computers with widescreen touch displays from several manufacturers are now available for under $1000, whereas the current Active Earth Display pages are designed for a fixed-resolution square screen. Existing pages will be adapted to scale gracefully to widescreen displays. In addition to allowing the use of low-cost, all-in-one touchscreen computers, this will also facilitate the deployment of non-interactive displays on flat-panel televisions. Over the funding period, the design of new pages will take advantage of widescreen aspect ratios, and work will begin on using resolution-independent technologies to replace fixed-size raster graphics. Resolution independence will also allow elements of the Active Earth Display to be deployed on new types and sizes of touchscreen devices such as touchscreen phones and media players, and tablet and pad-type computing devices. These "personal" touchscreen devices are rapidly becoming major platforms for media consumption and it is anticipated that they will become widely used as tools to deliver educational materials.

Develop New Content Modules and Content Creation Tools

One of the features that distinguishes the Active Earth Display from a passive web site system is the ability of end users to both configure which pages are displayed from IRIS, but also to add pages of their own. This feature allows, for example, users to develop pages that deal with local seismic or tectonic issues. Currently, users need to code pages directly in HTML and SWF formats. We propose to develop a toolkit that will allow end users to generate content by simply mixing their custom text and graphic images with preconfigured widgets and templates. IRIS E&O will subsequently host user-created content that is of high quality and broad appeal.

To facilitate nationwide dispersal of Active Earth Display systems, and to complement the progress of USArray's Transportable Array, new content modules will continue to be developed, including one on the seismicity and tectonics of the New Madrid region and one on seismicity and tectonics of the eastern margin of North America.

INCREASE IMPACT AND EFFICIENCY FOR SEISMOGRAPHS IN SCHOOLS

The experience gained during the development of the Seismographs in Schools program provides the basis for creating a much greater impact without increasing staff involvement. The revised approach will focus on developing resources to support regional centers, lead by local seismologists, and less national emphasis on interactions with individual teachers. For example, Kaz Fujita from the University of Michigan is developing a regional group based around the Michigan Earth Science Teachers Association. To ensure the effectiveness of this approach, sufficient teacher training will still be vital. However, it will be achieved through the regional networks rather than IRIS E&O in two ways. First, IRIS E&O staff will develop "train the trainer" resources to leverage the program's considerable experience developing individual teachers' skills and content expertise. Second, additional web-based training for teachers will be developed. This development has already begun with clips demonstrating how to assemble the instrument, and it will be expanded to videos covering more advanced processes and techniques (Figure A4.12). Web-based training will also include a curriculum sequence developed and tested by the Boston College Educational Seismology Project with partial funding through IRIS E&O. Additional leveraging will be achieved through the capabilities of improved software (Amaseis), with more classroom impact per sensor, and access to live research-quality

Figure A4.12. AS1 instructional video.

MEMS TECHNOLOGY IN THE CLASSROOM

The use of MEMS technology in the classroom integrates research and education and addresses the Grand Challenges recommendation to explore MEMS technologies to develop low-cost seismic sensors that can be deployed in great numbers and can supplement or replace current seismometers. The reduction in price and improvement in quality of the sensors is being driven by the computer gaming industry. The resulting sensors have already shown their usefulness as aftershock sensors for the 2010 M 8.8 Chile earthquake (Cochrane, 2010, personal communication).

data via the DMS. IRIS will also work with manufacturers to improve the hardware to make it more robust and easier for teachers to set up and maintain.

PORTABLE DEVICES AND INCREASED USE OF SOCIAL MEDIA VIA THE WEB

Mobile phones are becoming primary web information tools, while "the iPod, the most ubiquitous student tool, is enabling college students to tap into lectures on their own time, and in the K–12 space, podcasting is opening up the classroom to parents and to the community" (from http://www.techlearning.com/article/8328). To exploit these trends, IRIS E&O plans to begin developing resources for mobile devices. These resources will include simplified near-real-time information pages for mobile phones, new animations and videos, and educational materials that involve the motion sensors in most new devices. Audio podcasts will be created on topics including general seismology, IRIS Consortium research, and recent earthquakes. Initially, the podcasts will be produced for a general public audience, with a later focus on undergraduate-level topics. The podcasts will be designed to complement existing USGS podcasts.

The use of social media (e.g., Facebook, YouTube, Twitter) is an important new strategy, and its use will be expanded to both attract audiences already using those venues as well as draw them to the main IRIS web site for more detailed content. For example, the IRIS YouTube accounts have been a very popular venue for visitors to locate and use IRIS multimedia resources. As part of the move to more online professional development, animation and short video clip offerings will continue to be expanded.

Targeted input will also be provided to articles on Wikipedia, adding links to IRIS-related material. While changes to the IRIS web site have significantly raised IRIS's standing on Google searches in the past year, Wikipedia still is higher than IRIS for most seismology-related topics, so a larger audience can be reached by adding information and images to those pages.

IRIS's experience with collaborative development of SeisMac, which allows every Mac laptop to act as a seismograph, has led to collaboration with the Quake-Catcher Network (QCN), led by Stanford and UC Riverside. QCN uses low-cost MEMS accelerometers within, or external to, a laptop or desktop computer, and distributed computing to record earthquakes. QCN provides the cyberinfrastructure for individuals to actively collect scientific data and share in scientific discovery, while participants provide the physical infrastructure for the QCN sensors (e.g., computer, Internet, power). Currently, QCN has over 1,000 participants worldwide (Cochran et al., 2010, *Seismological Research Letters*, doi:10.1785/gssrl.80.1.26). QCN developed kinesthetic learning software similar to SeisMac that uses MEMS sensors for education. However, to become an effective educational tool, engaging modules are needed to target specific learning outcomes. Further, to fully utilize the sensors and software in formal educational settings, user interfaces and functionality need to be improved in a way that serves an educational audience, and both of these needs will be pursued under the current proposal through a subaward to Stanford/QCN.

Simple seismograph-like applications also exist for iPhones and other smart phones, but none has been designed specifically for educational purposes. IRIS E&O will work with the

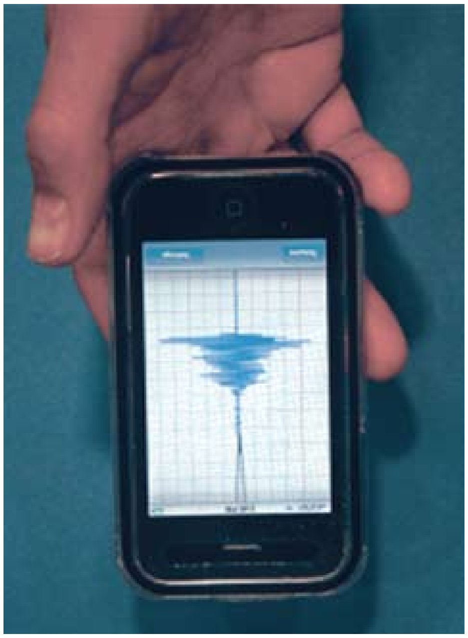


Figure A4.13. Sample iPhone seismograph app.

developers of these applications, as we did with SeisMac, to improve their educational value and integrate their use into IRIS educational modules. In addition, IRIS E&O will develop educational resources that can either be embedded in or linked to these applications to deliver supporting content once users have been hooked through experimentation with these devices. These tools will allow educators to use a wide range of devices to engage students in kinesthetic learning.

INTEGRATED ONLINE MIDDLE AND HIGH SCHOOL CURRICULUM

IRIS E&O has extensive experience with face-to-face professional development and the creation of new online educational modules that target gaps in available materials relating to seismology. However, a missing aspect of the web-based materials is that they do not communicate an approach to delivering content in the classroom, or promote instructor learning of subject matter, pedagogy, and pedagogical content knowledge, which are all elements identified as key components of effective curricula (Davis and Krajcik, 2005, *Educational Researcher*, 34(3):3–14). Further, these web-based resources lack an instructional sequence linking one activity to another. While existing sequences do exist, they are either dated (FEMA's Tremor Troops is 25 years old) or have been watered down to the "traditional staples" by textbook companies.

To address these needs and to greatly expand the impact and value of the existing IRIS educational resources, we propose to develop an online *Middle-School Teachers' Guide to Earthquakes and Seismology* in partnership with the University of Portland. This guide would feature learning sequences for: (1) basic plate tectonics, (2) an introduction to seismology and Earth structure, (3) fundamentals of earthquake seismology and earthquake hazards, and (4) regional plate tectonics and earthquake and tsunami hazards. Each learning sequence would feature a coordinated set of slide presentations, video lectures, computer animations, and classroom activities. Underpinning each learning sequence would be a novel web-based "instructor guide," promoting instructor learning of subject matter, including how to teach the material. The principal elements of this sequence are already available via the IRIS web site, the *Middle-School Teachers' Guide to Earthquakes and Seismology* DVD, and the TOTLE eBinder CD created by Robert Butler, or have been refined through IRIS's many years of delivering professional development. The next steps toward the development of this guide will occur through publication of a special issue of the journal *The Earth Scientist*, focused on seismology, in which the National Earth Science Teachers Association has invited IRIS to take the lead.

WORKSHOPS AND TRAINING FOR THE IRIS AND INTERNATIONAL COMMUNITY

IRIS E&O has extensive experience planning and implementing high-quality professional development experiences for teachers and non-IRIS Consortium college faculty. As part of the new strategic plan to support IRIS Consortium members, IRIS E&O proposes to combine that experience with IRIS community research and education expertise to provide workshops designed for Consortium graduate students and early-career faculty that are more data intensive. The presenters would be leading seismologists, and they would share cutting-edge analysis tools and techniques. An example of such a workshop is the USArray data processing short course held in 2009 and scheduled again for 2010. It is also proposed to develop a workshop targeted at Educational Affiliates that will focus on data use for undergraduates. The workshop will highlight the new analysis software and activities proposed in earlier sections. Another workshop for IRIS researchers and students will focus on shallow active-source seismology supporting the acquisition of new equipment by PASSCAL. In addition, IRIS E&O will work with the IRIS international development group to provide educational materials and help to provide support for capacity-building workshops.

HISTORICAL CONTEXT OF CURRENT OPERATIONS

The EarthScope facility operates on a dramatic scale—with literally thousands of instruments deployed in the field collecting terabytes of data that are distributed to thousands of users worldwide. IRIS operates the USArray component of EarthScope. USArray was completed on time and on budget as part of the initial five-year EarthScope Major Research Equipment and Facilities Construction (MREFC) phase of operations. The MREFC award was concluded in 2008 and at that time EarthScope transitioned fully into its current Operations and Maintenance (O&M) phase.

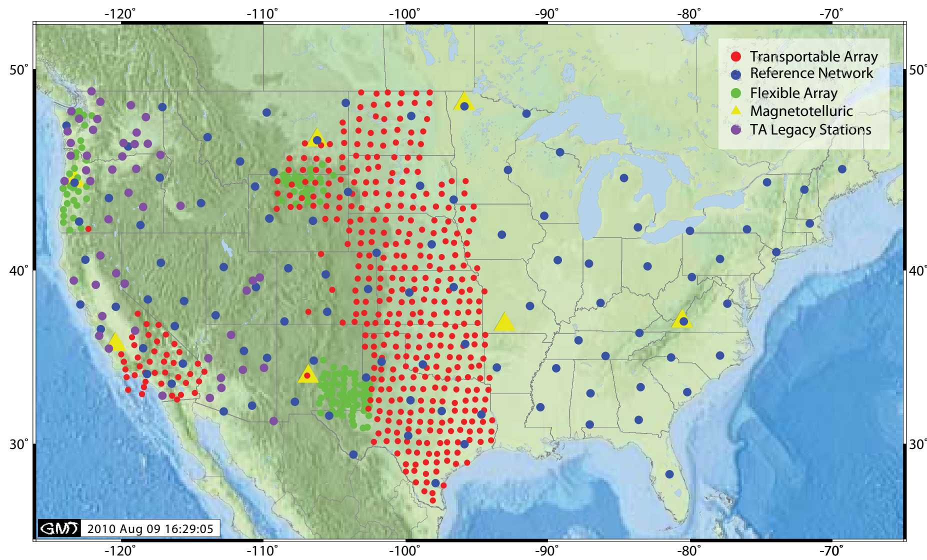


Figure A5.1. At-a-glance summary of the deployment of USArray instruments. For clarity, past FA deployments and MT campaign sites are not shown.

The EarthScope USArray facility consists of four observatory components (Figure A5.1): a Transportable Array of ~400 seismic stations; a Flexible Array pool of seismic instruments; a Reference Network of permanent seismic stations; and a Magnetotelluric observatory. USArray also includes comprehensive data management and siting outreach efforts.

TRANSPORTABLE ARRAY (TA)

The TA has occupied nearly 1000 sites across the western and central United States and continues its multi-year migration towards the Atlantic coast. The stations use a grid-like deployment with 70 km separation between stations. At any given time there are approximately 400 stations operational with each station being operated for two years before being relocated further east. Once the first 400 stations were completed in the western United States, the TA began to "roll." The TA has now been "rolling" for roughly three years, with ~18 stations deployed and ~18 stations removed every month, year round. Through the western mountains and now onto the central plains, the TA has stayed on budget and on schedule.

Each TA station is equipped with a three-component broadband seismometer (Figure A5.2). All data from the TA are collected in real time, and are subjected to a variety of automated and manual quality-control reviews. The data quality from TA stations has been extremely high, with low-noise performance that is very consistent across the array. The TA stations generate long, continuous (gap-free) time series with very high data availability. In 2009, the average data availability across the whole TA was 99.3%.

Figure A5.2. Installation of a Transportable Array station (left panels), instrumentation (middle and middle right panels), and completed station (right panel). The vault is under the mound of dirt in the foreground.

FLEXIBLE ARRAY (FA)

The FA has 346 broadband, 130 short-period, and about 1700 active-source instruments that are available for Principal-Investigator (PI)-driven experiments (Figure A5.3). The FA equipment pool is fully utilized, supporting a range of broadband, short-period, and active-source experiments. The FA provides essentially complete stations to the PI. It also provides data services that collate the raw data retrieved from the field and deliver these data, and their corresponding metadata, to the IRIS DMC. Data return from FA experiments has been 95%, on average. The combination of the large pool of readily available instruments coupled with full data-service support has resulted in very ambitious experiments. It is not uncommon for FA experiments to involve 75 to 200 stations for natural-source experiments, and many more instruments for active-source experiments. The scientific return from FA experiments has been enhanced through the joint interpretation of FA data in the context of the background observations provided by the surrounding TA station grid.

REFERENCE NETWORK (REFNET)

The Reference Network consists of ~100 stations located at ~300 km spacing across the continental United States to provide a fixed reference frame for the moving TA. The initial core of RefNet was the backbone network of the USGS Advanced National Seismic System (ANSS), supplemented with the USArray Permanent Array—a set of 39 stations that were installed or upgraded with USArray funds. These 39 stations have now become a permanent part of the USGS Advanced National Seismic System backbone network. To achieve a more uniform station coverage, the TA installed an additional 20 "advance deployed" stations (so named because many of the sites were installed to the east of the then-current TA footprint). The USGS is responsible for operation of the ANSS backbone network and USArray has no ongoing O&M responsibility or obligation for the RefNet stations, apart from the 20 TA stations that are considered part of the RefNet. These 20 TA stations will be operated for the duration of the USArray project.

MAGNETOTELLURICS (MT)

The MT component of USArray includes seven permanent observatories spanning the continental United States, as well as 20 station equipment sets that are deployed campaign-style each summer (Figure A5.4). During the summer campaign, each of the 20 portable station sets is deployed at two to three different locations on a 70-km station spacing grid (similar to the seismic TA), for about three weeks per location. Data have been collected from 221 temporary sites in the northwest quadrant of the United States over the past four summers. The MT effort has performed noise comparison tests to evaluate different electrode designs, and has standardized the production of uniform, consistent electrodes. Data quality has been high, with the permanent stations achieving response functions to periods of 100,000 s or more, and virtually all of the temporary sites yielding usable transfer functions (despite the last couple of years being in a solar minimum, which has greatly reduced source levels).

DATA MANAGEMENT (DM)

USArray data are archived and distributed via the IRIS Data Management Center. Over 27 terabytes of EarthScope seismic data have been archived to date, and these data are distributed at rates exceeding 8 terabytes per year. All USArray data are made available through the request tools supported by the DMC, and the TA data are also served through the real-time data streaming protocols supported by the DMC. USArray data usage has been very high, with more than twice

Figure A5.3. Training the deployment team at the beginning of an FA experiment.

FigureA5.4. Students installing magnetotelluric system during summer field campaign.

Figure A5.5. Participants in siting workshop jump to demonstrate the sensitivity of the nearby seismometer

Figure A5.6. Active Earth interactive touch-screen kiosk. Kiosks like this one have been loaned to institutions in states where the TA is currently active. This one is located at the University of Nebraska-Omaha.

as much data being delivered to researchers as is collected. There are hundreds of different users of USArray data every month, with some users obtaining USArray data at the rate of hundreds of gigabytes per month.

SITING OUTREACH (SO)

The Siting Outreach component of USArray is implemented in collaboration with IRIS E&O to facilitate siting of USArray stations and works with numerous state and local organizations to encourage the use and understanding of USArray. University PIs and students are recruited every summer to do the initial reconnaissance for TA stations sites. Over the last several summers, more than 100 students from 38 different universities have done site reconnaissance on 970 different TA stations sites. To further broaden the reach of USArray, the SO team works with the PIs and their respective Communications Office to issue press releases about their involvement in EarthScope. This activity has generated significant interest from local news media and has resulted in a growing number of print, online and broadcast stories about the project, including an article in *USA Today* in June 2010. The SO team also produces and distributes *onSite*, a publication prepared twice each year to communicate news about USArray and EarthScope to more than 1100 current and former hosts of Transportable Array stations. Additionally, SO has helped organize science cafes and workshops (Figure A5.5), developed content for the Active Earth Display interactive kiosk (Figure A5.6), loaned Active Earth Display kiosks to sites in the USArray TA footprint, and distributed AS-1 seismometers to teachers and trained them in the use of these instruments (Figure A5.7).

Figure A5.7. Teachers locate an earthquake during an EarthScope Workshop

INITIATIVES UNDER THE CURRENT COOPERATIVE AGREEMENT

Innovation is a fundamental element of USArray activities, because there is little or no precedent for seismological and magnetotelluric operations on the spatial and temporal scales of USArray. USArray's basic operating characteristics, such as the numbers of instruments and the number of station sites occupied per year, are defined under the current five-year Cooperative Agreement with NSF. A control process is used to manage changes to these activities. However, within the broad operating objectives of USArray's current Cooperative Agreement, there have been a number of innovations and initiatives aimed at enhancing data quality, data availability, and scientific value.

CASCADIA INITIATIVE

The USArray component of NSF's Cascadia Initiative is being undertaken as a special ARRA-funded supplemental activity under the existing Cooperative Agreement. This initiative is aimed at addressing fundamental questions about episodic tremor and slip and other processes along this important subduction zone. As part of the initiative, the TA has re-installed 27 TA stations along the Pacific coast, from the Canadian border to northern California. Besides the TA stations, the Cascadia Initiative will include the upgrade of some 232 Plate Boundary Observatory GPS stations to higher-rate sampling and will include 60 ocean bottom seismometers deployed offshore, in both shallow and deep waters. The TA stations are being sited with careful consideration given to the locations of any existing broadband stations so that the uniform station coverage of Cascadia is achieved.

Each of the TA stations deployed as part of the Cascadia Initiative is equipped with three-component broadband and strong-motion sensors. Data flows into the IRIS DMC and is part of the TA data flow. Virtual Network Definitions for the Cascadia Initiative have been set up to facilitate making single data requests to obtain all relevant Cascadia seismic data (the VND will include the offshore stations as well, once the data and metadata have been archived).

ATMOSPHERIC PRESSURE AND INFRASOUND OBSERVATIONS

To leverage the TA as a large-scale observing platform, investigators at UCSD sought and obtained NSF MRI funding to augment every TA station with barometric pressure and infrasound sensors. In effect, the TA becomes a telescope looking upward as well as downward. The regular grid of barometric pressure sensors will support studies of mesoscale atmospheric dynamics and the relation of pressure variations to seismic signals (e.g., tilt on the horizontal seismic components). The infrasound sensors will measure signals from energy that propagate long distances in Earth's upper atmosphere. These sensors will provide an order-of-magnitude increase in the worldwide infrasound station sites, providing observations of unprecedented spatial extent.

TA STATION DESIGN

The TA is engaged in a continuous, ongoing effort to refine station designs to provide uniform, high-quality, high-reliability stations. The TA has engineered refinements to vault design, such as the Vault Interface Enclosure (VIE) that enhances reliability. This design shields delicate parts from ambient conditions, reduces costs by providing a single hardened environment for multiple small components (saving costs on the packaging of the individual components), and provides comprehensive power management that improves station reliability. The VIE project is only a single example of the continuous refinement in procedures and practice that is part of the "rolling" of the TA. Enhanced collaboration between USArray, GSN, and PASSCAL under the Instrumentation Services component of the new RIS management structure, will help ensure that design refinements like these will be coordinated across all IRIS programs.

NEW OPPORTUNITIES AND DIRECTIONS

The approaching integration of the IRIS Core program and USArray Cooperative Agreements presents an opportunity to build on USArray's success to date. A tight integration already exists between USArray operations and the IRIS core programs. This relationship has been a key element to USArray's success while simultaneously enhancing the IRIS core programs. A unified Cooperative Agreement will provide an opportunity to further align management activities and practices, while at the technical level, it will reinforce the strong integration that already exists. A unified Cooperative Agreement places maximum importance on the net scientific return from the IRIS infrastructure by reducing programmatic differences and increasing efficiency.

By its original design, USArray leverages the existence and expertise of IRIS core programs by integrating activities wherever possible. Such integration played an essential role in the construction phase of USArray—providing a functioning and experienced management and infrastructure that allowed USArray to get off to a fast and efficient start while allowing the core programs to accommodate the growth associated with USArray-related activities in a holistic fashion. Several examples of the integrated USArray-IRIS core activities include:

- The FA effort shares facilities and personnel with the IRIS PASSCAL program. This arrangement makes efficient use of the specialized infrastructure and expertise that was initially developed to support PASSCAL. Both FA and PASSCAL investigators benefit from innovations developed in either program. A unified Cooperative Agreement will improve the structure for cost sharing of development activities that benefit both programs.
- USArray data management activities are provided within the context of the IRIS DMS. Setting up separate data management system for USArray would have been redundant with DMC services and would not have realized the economies of scale inherent in the DMS. The USArray waveform quality-control effort is, in part, based at the DMC and has enhanced the DMS program's expertise in this important area.
- USArray's siting outreach activities are managed and staffed by personnel shared with the IRIS E&O program. The E&O program incorporates a wide range of highly specialized expertise in outreach related activities. This relationship has allowed USArray to tap into a far greater range of expertise and resources, on an as-needed basis, than it otherwise could. The two programs, working together, have been able to take on several initiatives that would have been too large for either program individually—such as the Active Earth Display work and the development of the Teachable Moment slide sets.
- During the MREFC phase of USArray, the construction and upgrade of Permanent Array stations was facilitated by the IRIS GSN program staff and their network partners.

USArray and IRIS core program technical performance and scientific return are high. The existing, robust scientific/programmatic advisory structures are key to maintaining this high performance. USArray has a well-developed advisory structure, and the IRIS core program standing committees also feel a strong sense of involvement and ownership of USArray. The unified Cooperative Agreement will ensure that the advisory structure framework is integrated and adapts to the evolution of the programs.

A single Cooperative Agreement will also improve synchronization of the budget process across the USArray and IRIS core programs, facilitate both program planning and execution, and streamline the process for sharing resources.

6 | INTERNATIONAL DEVELOPMENT SEISMOLOGY

HISTORICAL CONTEXT OF CURRENT OPERATIONS

Although IRIS was founded as a consortium of U.S. research institutions, the outlook of its members and the scope of its activities have been international from the earliest days. Discovering deep Earth structure, mapping the complexity of continental and oceanic lithospheric structure, and studying great earthquake rupture all require a global perspective. An example of this perspective is that data from USArray—which was envisioned as a facility to study the North American continent—have been used to gain new insights about rupture of earthquakes around the world, the dynamics of the inner and outer core, and other subjects.

The scientific impetus toward a global perspective has led numerous individual investigators and the IRIS facilities to embrace an international approach. Close and long-term collaborations with colleagues from countries in virtually every region of the world have been essential to achieving the goals of research projects and to creating facilities that support such projects. A large majority of GSN stations are located outside of the United States and many rely on local hosts for reliable operation. About half of all PASSCAL deployments are abroad. DMS manages data from geophysical networks worldwide and serves users in dozens of countries. E&O collaborates with educators in many countries.

Seismology abounds with broader societal impacts: seismologists are Earth scientists with observational tools and quantitative skills that are used in numerous applications, including natural hazard mitigation, resource discovery, national security, and environmental change. It is not surprising that the nature of these impacts is different in developing countries, holding the possibility of even more profound benefits to both science and society.

Figure A6.1. The first DMS Metadata Workshop was held in Palmonova, Italy during 2006. It brought together seismologists from Africa, the Middle East, and Central Asia. Subsequent workshops in Brazil, Malaysia (above photo), and Egypt have helped seismologists in developing regions around the world to achieve new standards in data management.

International Development Seismology (IDS) constitutes one IRIS interface between its NSF-sponsored scientific mission and the imperative to ensure that scientific progress enables socially important outcomes. The specific focus of this effort responds to the recognized importance of developing the partnerships, technical infrastructure, and human capacity required for effective international cooperation, not only as an instrument to accelerate scientific progress through collaboration with technologically equal partners, but also as an essential element of various other modes of U.S. foreign engagement, including foreign assistance and science diplomacy.

In this context, although IDS activities are not directly discovery-oriented, they are closely aligned with those identified in NSF's organic authorizing legislation to initiate and support specific scientific and engineering activities in connection with matters related to international cooperation, national security, and the effects of scientific and technological applications upon society.

Because IDS goals span the boundary between knowledge expansion and its societal impact, IDS is conceived to be only partly dependent on NSF/EAR support. NSF-sponsored IDS activities are thus designed to serve as seeding efforts or pilot projects targeted toward achieving two complementary, synergistic goals. The first goal is to aggressively promote strategies that support fundamental research and exploration through wide and reliable geographic coverage. The second goal is to contribute to reducing global population exposure to seismic hazards through broad education of scientific and technical principles that have an impact on societal resilience through increased awareness, preparedness, and accountability.

IDS evolved from the charge to the IDS Committee created by IRIS Board of Directors in 2008 upon the recommendation of the International Working Group. The recommendation emerged as an IRIS community response to address two complex challenges:

Figure A6.2. One of IRIS's long-term instrument loans was to permanently improve monitoring on the Nicoya Peninsula, Costa Rica, by helping Universidad Nacional to re-occupy vaults that were constructed for PASSCAL experiments. Here, Victor Gonzalez of UNA services a station that part of a cooperative, multi-disciplinary project with the University of California, Santa Cruz, to monitor Arenal Volcano. Other instruments were loaned to AfricaArray, the University of Bangladesh, the Kyrgyzistan Seismic Network, and Instituto Nacional de Prevención Sísmica, Argentina.

1. To leverage U.S. investment in advancing scientific understanding of some of the most complex tectonic systems on Earth by engaging the sustained and active participation of low- and middle-income countries located in these territories in the necessary expansion of modern seismological research capability
2. To address the social responsibility of the scientific community to facilitate the translation of new knowledge into societal benefits, by contributing to efforts toward sustainable development of low- and middle-income countries partly through the mitigation of population exposure to seismic hazard

The potential for special approaches to return greater scientific and societal benefits was widely recognized in responding to the 2005 Sumatra earthquake and Indian Ocean tsunami. IRIS has undertaken several activities that build on this potential, including participation of GSN and PASSCAL staff in training programs, organizing data management workshops for seismologists in developing countries, and making long-term loans of selected and reconditioned PASSCAL instruments to leverage other contributions that improve seismological monitoring networks in developing countries.

CURRENT OPERATIONS

IDS activities are undertaken with the advice and guidance of the IDS Committee and Board of Directors in response to IRIS community international engagement needs.

The ability to promote effective, large-scale engagement of foreign national resources in local seismological development depends on circumstances often unique to each country. The success of any efforts designed to promote the sustainable development of national or regional capacity in geophysics depends on a solid understanding of national institutions and policies and the cultural environment in which the scientific activities will take place. IDS initiates and maintains communication with appropriate foreign governments and officials as well as academic and research leaders to identify optimal strategies to support seismological development in selected countries. IDS identifies partner national, foreign, and international government and nongovernmental organizations (NGOs) that share IRIS scientific goals and objectives, or whose development goals and objectives complement the IRIS mission, and develops an in-depth functional understanding of these organizations to establish suitable partnerships.

While it is valuable to identify alternative funding sources from the country of interest, suitable funds often originate from other high-income countries sharing common scientific and development goals with the United States. IDS identifies non-traditional or small-scale science funding sources in the United States and abroad to leverage NSF scientific investment in seismological research in foreign countries. IDS initiates and maintains communication with key officials in U.S. government agencies, professional societies, and NGOs responsible for international cooperation not only in geophysics, but in science in general, to identify trend and policies that may result in funding and collaborative opportunities for IRIS and its Affiliates. IDS pursues funding or in-kind support to leverage NSF seeding funds for IDS activities from non-traditional funding sources, and for negotiating the terms and conditions of this support while ensuring that scientific objectives remain central to each activity.

DEVELOPMENTS UNDER THE CURRENT COOPERATIVE AGREEMENT

Given the success of the AfricaArray Project (a collaboration among Penn State, the University of Witwatersrand, and the South African Council for Geosciences), in 2008, IRIS convened a workshop—*Out of Africa*—that focused on adapting the AfricaArray model to other regions of the world. Expanding education was identified as the most important issue for geophysics in developing countries. As a consortium in which the member organizations are almost all institutions of higher learning as well as research, IRIS is well suited to address this priority. However, with activities related to seismology in developing countries distributed across all of IRIS, the need to coordinate efforts among diverse IRIS activities and with external organizations was identified. Consequently, the International Working Group recommended to the IRIS Board of Directors the creation of the IDS Committee and the hiring of a Director of IDS.

Over the past two years, IDS activities have spanned from exploratory meetings, to collaborative projects, to multidisciplinary activities in response to destructive earthquakes. Additional efforts have focused on pursuing funding for capacity-building and transitional activities across the science-policy boundary.

The outstanding finding from a joint meeting of the (Centro Regional de Sismología para América del Sur (CERESIS) and the IDS Committee in Lima, Peru, during 2009 was the remarkable heterogeneity of conditions for conducting geophysical research, as well as earthquake monitoring and preparedness, among individual countries in South America. The conclusion was that effective seismological development in the South American region requires the design of strategies tailored to various unique national conditions. Upcoming IDS activities are planned to outline country-specific seismological development strategies in collaboration with identified scientific and academic leaders.

The devastating earthquakes in Haiti on January 12, 2010 (Mw 7.0) and in Chile on February 27, 2010 (Mw 8.8) dramatically highlighted the significance of socially responsible scientific foreign engagement and largely impacted the nature of IDS activities in 2010. These unforeseen IDS activities have received unexpected generous cross-sector support from U.S. government and nongovernmental organizations, establishing partnership models that demonstrate the feasibility of enhancing the value of NSF scientific investment.

The enormous post-earthquake challenges in Haiti demanded close interaction among the assistance, engineering, and scientific communities from the early stages of the recovery and reconstruction. In light of this challenge, the U.S. National Science and Technology Council's Subcommittee on Disaster Reduction requested IRIS assistance in convening an international, multidisciplinary

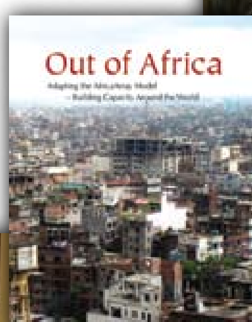


Figure A6.3. Seismologists from Southeast Asia, South America, Central America, and the Caribbean Sea Region at the Out of Africa workshop agreed that expanded education programs are the highest priority to improve geophysical capacity around the world.

Figure A6.4. To explore pathways for international cooperation leading to improved seismological capacity in South America, members of the IDS Committee met with representatives from nine CERESIS member countries.

FigureA6.6. IRIS acted as the Workshop organizer for "Rebuilding for Resilience: How Science and Engineering Can Inform Haiti's Reconstruction."

Figure A6.5. Haiti's earthquake on January 12, 2010, presented unprecedented challenges to the science and engineering communities, to government agencies and nongovernmental organizations providing immediate relief as well as to those involved in longer term reconstruction. Photo credit: Walter Mooney, USGS and cross-sector workshop entitled "Rebuilding for Resilience: How Science and Engineering Can Inform Haiti's Reconstruction." This workshop was cosponsored by the U.S. Department of State, the U.S. Agency for International Development, and the United Nations International Strategy for Disaster Reduction, and held at the University of Miami on its Coral Gables, Florida, campus.

Free and open access to data from deployments in Chile by several different countries was a significant achievement during the response to the Chile earthquake. IRIS received support through the NSF RAPID funding mechanism to install a portable network of 60 stations in the aftershock zone of the Chile earthquakes and closely collaborated with Chilean, French, German and British groups in coordinating site selection and data exchange. IDS contributed to the aftershock monitoring effort by securing supplemental support from the U.S. Department of Defense Southern Command in the form of no-cost transportation of equipment, and assisting with in-field logistic arrangements during service runs. The success of this participation demonstrated the ability to negotiate cross-sector support for scientific projects and establishes a valuable precedent for future cross-agency engagement.

The main focus of IDS is to support and facilitate activities of transitional nature between scientific progress, impact, and development. This requires the consolidation of resources derived from diverse stakeholders often unaware of their overlapping interests. Under the current Cooperative Agreement, IRIS has prepared and submitted proposals to support these types of activities. Notably, various organizations have approached IRIS to offer leveraging of financial support, highlighting current broad interest in scientific capacity as an integral component of development.

One of these activities is entitled "Geophysical Hazards and Plate Boundary Processes in Central America, Mexico and the Caribbean: A Workshop to Build Seismological Collaboration and Capacity." This workshop, to be conducted in Heredia, Costa Rica, in October 2010 (with support from NSF Office of International Science and Engineering (OISE), USGS, USAID and State Department), will bring together seismologists from Central America, Mexico, the Caribbean, and the United States to plan and coordinate initiatives that will contribute to seismological research and hazard mitigation within the region. The workshop goals include developing a roadmap for research leading to regional site characterization products, "ShakeMaps" for scenario and actual earthquakes, and models of seismic velocity; making concrete plans for new science initiatives with tangible benefits to broader society, including regional data sharing, increasing regional geophysical expertise, and improving existing seismographic networks; and new

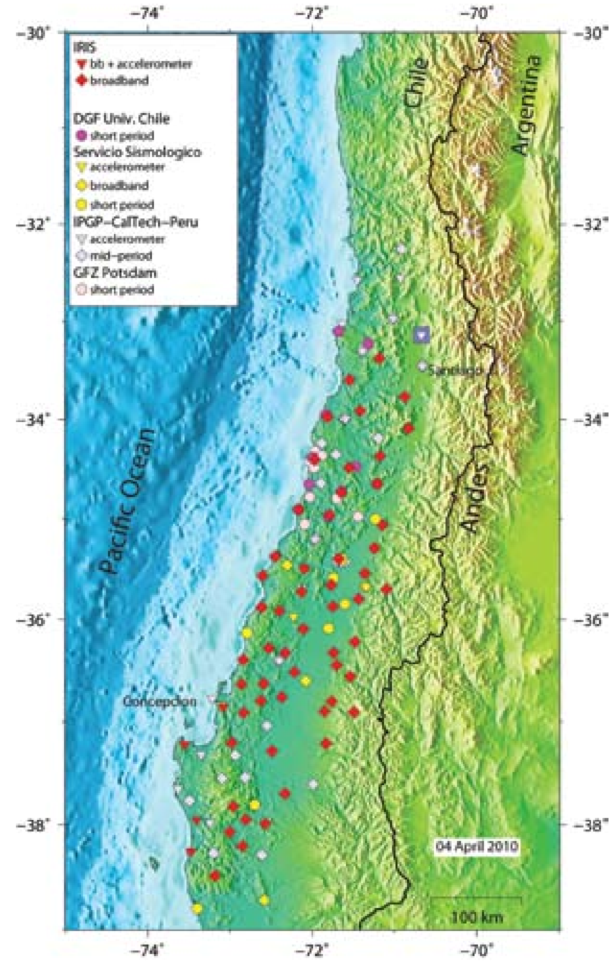


Figure A6.7. Following the February 27 earthquake in Chile, IRIS worked on behalf of its Members with scientists from U.S. universities and the University of Chile on the deployment 58 portable instruments funded by a RAPID award from NSF and coordinated closely with investigators from France and Germany.

scientific collaborations to address key questions regarding plate boundary processes in the diversity of tectonic environments of the region.

A second activity is the "Pan-American Advanced Studies Institute on New Frontiers in Seismological Research: Sustainable Networks, Earthquake Source Parameters, and Earth Structure" Institute to be held in Quito, Ecuador, in July 2011, with primary funding from NSF OISE. This Institute will focus on strategies for developing and maintaining modern seismological observatories and exploring recent advances in the analysis of seismological data in support of basic research, education, and hazard mitigation. The Institute is designed to engage graduate students, postdoctoral researchers, and new faculty from across the Americas in an interactive collaborative learning environment. The Institute's primary objectives include developing an understanding of the principles of sustainable network operations; promoting open access and data exchange within and between countries in support of research, education, and hazard mitigation; and examining recent advances and current challenges in characterizing earthquake sources and imaging Earth structure. The Institute can contribute to development of a guide to sustainable network operations, an inventory of networks in the Americas, and an index of data product software.

Other IRIS international activities, such as the DMS data management workshops, the training of co-investigators from abroad to assist in temporary deployments, and working with local operators of GSN stations have continued under the current Cooperative Agreement. Moreover, IRIS continues to look for opportunities to promote data exchange by sharing software, developing standards, cooperating with data management organizations in technologically sophisticated countries, and by seeking innovative approaches to managing data from AfricaArray and other networks in developing countries. As exemplified by the Central Asia Data Exchange project initiated by the DMS, IRIS has also made extra investments of staff time and financial resources where a focused effort in a developing region seems especially likely to have a high impact.

NEW OPPORTUNITIES AND DIRECTIONS

The long-term goal of IDS is contributing to the understanding of Earth systems through the development of reliable and sustainable seismological research capacity with global coverage. Within the next decade, IDS objectives are to promote the development of nationally operated, sustainable seismological networks in low- and middle-income countries. Between July 2011 and September 2013, IDS will develop and solidify the functional structure necessary for the systematic expansion of ongoing pilot initiatives. Specifically, IDS will focus on two areas. One will be the continuous support of ongoing existing international activities led by IRIS facilities and IRIS Members in multiple geographic regions. The other will be to test a practical model for systematic promotion of seismological research capacity development in a select set of middle-income countries. The expectation is that it will be possible to reproduce and adapt this operational principle to countries in other regions and various development stages.

Seismology research in low- and middle-income countries can be conducted under a wide range of schemes, spanning from complete national autonomy to full dependence on foreign human, technical, and financial resources. The ratio between foreign and domestic involvement generally depends on a combination of economic and political factors that are unique to each country or region. Awareness and understanding of these unique circumstances will be crucial to the success of development initiatives.

IDS will develop and implement comprehensive protocols in pursuit of the IRIS mission, encourage foreign national investment in seismological research and monitoring, forge sustainable bilateral partnerships with national academic and research institutions, and government agencies, and foster the development of regional international seismic networks. Through active participation and support of these investments, IDS looks to promote the use of current standards for network operations, data formats and exchange protocols, and the pursuit of policies of free and unrestricted data access.

Near-term efforts will be driven by opportunities that arise from recognition by developing countries of the potential economic and humanitarian benefits from geophysical capacity building. Initially, IDS may focus on the Pacific Rim countries in South America (Chile, Peru, Ecuador, and Colombia) and Bolivia. The rationale for this region is that the seismic hazard in all of these countries is great, they have sufficient academic and intellectual absorptive capacity, and they present low logistic difficulty. As this proposal is being completed, IRIS has been informed by NSF that an MRI proposal will be funded to install a backbone network of ten geophysical observatories to augment the new Chilean National Seismic Network. It is hoped that this joint project between IRIS and the University of Chile will provide a model for similar collaborative development efforts in other countries, both in South America and worldwide.

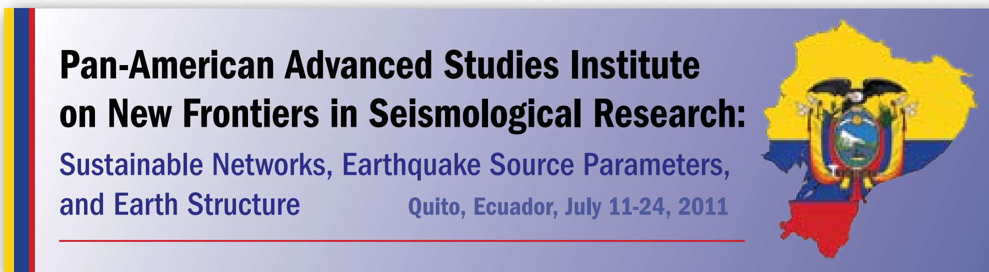
This multistep national and regional development strategy will focus on collaborations with leading seismologists from academia and government agencies in each country and on identifying the best strategy to support the development of national sustainable seismologic networks. The IDS Committee and staff will assist and support the identified leading scientist to pursue the resources necessary for network development and operation. This will likely involve convening country-specific workshops with respective stakeholders to identify all appropriate country leader(s); outline the best course of action; design a five-year plan and budget; identify instrumentation, training, education and outreach needs; and, importantly, assist foreign counterparts in seeking financial support from international donors.

PARTNERSHIPS FOR INTERNATIONAL DEVELOPMENT

Development of seismological capacity and research in low- and middle-income countries presents both a unique challenge and the opportunity to impact general economic development through scientific progress. Meeting these challenges and opportunities requires multisector and international partnerships that leverage U.S. scientific investment. Over the past year, IRIS has successfully engaged broad support for international science initiatives in collaboration with its member institutions and foreign affiliates.

Funded by NSF and USAID

Funded by NSF, USGS, USAID, and the U.S. Department of State



Funded by NSF

7 | POLAR SUPPORT SERVICES

HISTORICAL CONTEXT OF CURRENT OPERATIONS

Of critical importance to humanity is the assessment, understanding, and prediction of environmental change in the polar regions, especially pertaining to the fast- responding elements of the cryosphere. IRIS has had a long history of involvement in the polar studies, including operation of GSN stations in Antarctica, northern Canada and Alaska and support for a variety of portable studies of the crust and lithosphere in Antarctica and Greenland. In recent years, there has been increasing IRIS involvement in cryosphere observations including seismic signals indicative of Earth's changing ice masses and the collection (using active seismic methodology) of seismic data needed to constrain input data used in glaciological forecast models (e.g., measuring sub-ice-shelf seabed elevations and examining sub-ice-stream deformable sediments and lake distributions). These efforts are important because the icy regions of the planet, particularly alpine glaciers, Arctic sea ice, and the marine ice margins of Greenland and Antarctica, are among the most rapidly changing elements of all Earth's environmental systems.

The response of glaciers and ice sheets to climate change is critically important, but poorly understood. Climate change affects ice sheets, which in turn affect climate, and ice discharge from major polar glaciers and mountain glaciers makes a significant contribution to sea-level change and ocean circulation patterns. The Intergovernmental Panel on Climate Change (IPCC) currently estimates that approximately half of Greenland's contribution to sea-level rise comes from dynamic processes such as the discharge of ice from outlet glaciers, which is indirectly tied to surface warming and melting through hydrological feedbacks. But, the possible effects from rapid changes in the dynamic behavior of the ice sheet and glaciers are insufficiently understood—so much so, that the IPCC decided that it was still not possible to issue estimates of large-scale ice sheet contributions to sea-level rise over the next 100 years. In Greenland, the largest outlet glaciers have rapidly and dramatically changed during the last few years, with their mass loss leading to a doubling of Greenland's current contribution to rates of sea-level rise. Variations in glacier flow speed (over time scales from minutes to years) lead to large internal deformations that include dynamic thinning of the ice. Understanding the physical controls on outlet-glacier flow, and the time scales of response to climatic forcing, is necessary for proper modeling of the transfer of freshwater from the polar ice caps to the world's ocean.

Figure A7.1. Helheim glacier, Greenland, on August 19, 2008, during a large calving event that generated a glacial earthquake. View is to the south; glacier flow is to the left (east). In this photograph, the iceberg has reached a horizontal position, exposing its full thickness (~700 m). The height of the calving face is ~70 m. Photo courtesy of M. Nettles.

The glacial processes relevant to the interplay between ice and climate, and between climate change and sea-level rise, generate seismic signals. These seismic signals—both impulsive events and emergent tremor—are associated with internal "viscous flow" deformation of the ice in response to gravitational driving stresses, sliding of ice across a basal substratum that is influenced by subglacial hydrology that induces its own forms of seismic signals, disintegration and capsize of icebergs at the calving front, and drainage of supraglacial lakes into englacial and subglacial conduits. All of these processes are integral to the overall dynamics of glaciers, and seismic signals thus provide a quantitative means for both understanding the processes and for monitoring changes in their behavior over time. Long-term seismic monitoring of the ice sheet can also contribute to identifying possible unsuspected mechanisms and metrics relevant to ice sheet collapse, and could provide new constraints on ice sheet dynamic processes and their potential roles in sea-level rise during the coming decades.

In addition to climate-specific seismology, it is clear that global observatories in the polar regions, at best, provide sparse coverage for the study of the axial symmetric properties of Earth's interior. With only five GSN stations in

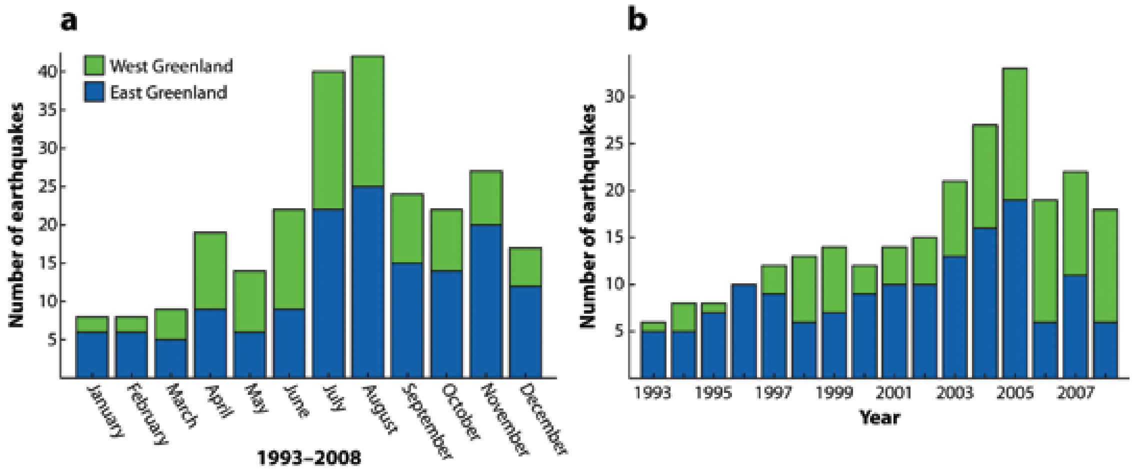


Figure A7.2. (a) Histogram showing seasonality of glacial earthquakes in Greenland based on detections for 1993–2008. Bars show the number of earthquakes per month detected in Greenland. (b) Histogram showing the number of glacial earthquakes detected in Greenland each year since 1993. From Figure 3 in Nettles and Ekström. 2010. *Annual Review of Earth and Planetary Sciences* 38:467–491.

Antarctica delivering real-time data, there are significant gaps in coverage for high-resolution, deep Earth structural studies beneath this large continent. Although international colleagues operate a handful of seismic stations around the perimeter of Antarctica, very few are offered in real time and all are subject to previous limitations of being collocated with scientific bases of operations, and thus are subjected to increased background noise contamination typical of generator-powered camps. Adding to the noise problem is the fact that most of these stations are near the ocean, subject to coastal noise. Similarly, Northern Hemisphere coverage is further limited due to the lack of landmasses for simple installations at the northern axis. In both cases, enhanced permanent station coverage will require the further development of remote, autonomous, real-time observatories that will operate in extremely harsh climates with minimal logistics support.

IRIS Polar Support Services (PSS) has facilitated this emerging area of seismologic interest by designing observatories that can be moved from teleseismic distances—thousands of kilometers away—to regional and local distances—hundreds to tens of kilometers and can operate robustly in the extremely cold, windy, high-altitude, and high-latitude environments. Instrumentation that can operate on or near the ice vastly improves the quality and quantity of high-definition signal recorded from glaciers. By incorporating state-of-the-art seismometers into these extreme designs, we retain the high-fidelity ground motion recordings required for concurrent global/teleseismic observations. In addition to the observatory equipment, the personnel ready, willing, and able to design and fabricate this unique equipment, and deploy it in these harsh environments, are highly specialized. To operate observatories under these conditions requires advancing the capabilities of the IRIS facilities above and beyond the "standard" station work currently supported.

IRIS founding principles are not only related to the collection and distribution of seismological data, but also the education of the seismological community. As we improve our capabilities in polar regions, we have the ability to offer education and engineering support to our national and international colleagues in successful deployments of polar seismological experiments. IRIS currently provides design drawings and documentation on this polar work, which are free and open to all (for online versions, go to http://www.passcal.nmt.edu/content/polar-programs) and consultation to other science disciplines such as climatology, glaciology, and physics.

With the increased interest in the study of polar environments, IRIS has developed capabilities that have allowed seismologists as well as glaciologists access to year-round broadband seismic data from study areas previously out of reach. With successes of the AGAP and POLENET Antarctic experiments, there is growing interest in expanding studies in these areas and enhancing permanent observations around

Figure A7.3. Deployment of MRI-developed autonomous station as part of the POLENET experiment, western Antarctica (photo courtesy of B Bonnett).

Earth's poles. With the new capabilities IRIS has developed, we have opened doors in the ability to study with high resolution, seismological phenomenon associated with the delicate polar regions. As such, the gap between the traditional global-scale permanent observatories (GSN) and regional, temporary experiments (PASSCAL) has been bridged, creating a capability to operate permanent regional- to local-scale observatories in polar climates. This resource will allow further understanding of bi-polar climate-related seismological phenomenon and improve the study of axial symmetric global properties in these sparsely covered areas of Earth.

With sustained core support, PSS will be able to continue development efforts for improved cold region systems as part of ongoing field support. This team could form the core of a more active design group, available to respond on a project-specific basis for enhanced design requirements identified by the community, including polar observations in many geophysical disciplines.

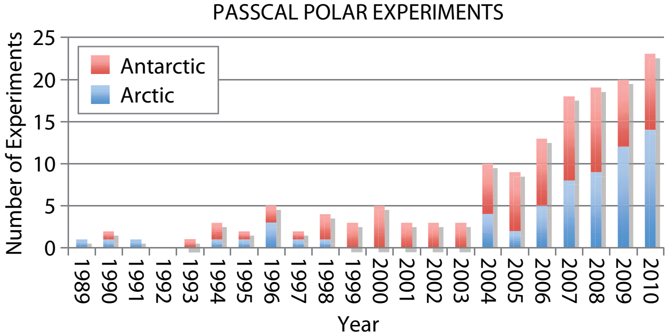
DEVELOPMENTS UNDER THE CURRENT COOPERATIVE AGREEMENT

ENHANCED POLAR-SPECIFIC CAPABILITIES

Over the past several years, the NSF Office of Polar Programs (OPP) has made a large investment to establish more robust capabilities at IRIS for seismological observations in extreme polar environments. With MRI awards for development (*Development of a Power and Communication System for Remote Autonomous GPS and Seismic Stations in Antarctica*) and acquisition of cold-hardened equipment, IRIS has successfully designed and developed smaller, lighter, and more robust observatory platforms that have greatly improved data return from experiments in the most remote and extreme parts of the Arctic and Antarctic. With these new capabilities, IRIS established Polar Support Services (PSS) at the PASSCAL Instrument Center (PIC) to retain specialized personnel, not only to support funded polar experiments, but also to maintain the polar observatory infrastructure and equipment as technologies continue to evolve and experiments are requested that continue to push the requested capabilities of the platforms.

The last five years have seen a significant increase in both the number of polar experiments and the time PIC staff spends supporting these experiments. Of approximately 60 experiments the PIC supports per year worldwide, now 10% to 20% receive funding from OPP. Standard support for experiments includes a suite of services, from equipment testing and maintenance, to shipping and handling, to data archiving. Polar projects require a level of support beyond what is supplied as standard, including cold-related engineering solutions, equipment fabrication and preparation for extreme conditions, and extended field support—often many man-months in the field, which is far beyond the field support that is typical for other experiments.

Although IRIS has been supporting PI-driven experiments in polar regions since 1989, it wasn't until the early 2000s that significant, over-winter seismic deployments were considered. In order to ensure a high level of data return and data quality for these OPP-funded projects, the PSS group focuses on: (1) developing successful cold station deployment strategies, (2) collaborating with vendors to develop and test -55°C rated seismic equipment, (3) establishing a pool of instruments for



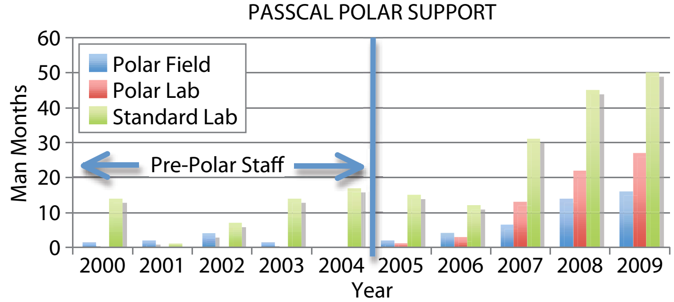


Figure A7.4. Number of polar experiments supported by IRIS PASSCAL (left) and number of person-months spent on support (right). Support is broken out into three categories: Polar Field = time spent in-field supporting polar network installations; Polar Lab = specialized lab preparations for polar experiments largely performed by OPP-funded positions; Standard Lab = routine procedures provided for all PASSCAL experiments and proportional to the total number of stations.

MONITORING OF HIGH-LATITUDE STATIONS

Using Iridium technology through design work contracted with Xeos Technologies (Halifax), the IRIS Polar Support Service group has develop command, control, and monitoring web interfaces to permit remote monitoring of high-latitude seismic stations. Work is underway to allow continuous data to flow through these same links.

use in cold environments, (4) building a pool of cold station ancillary equipment, and (5) creating an open resource repository for cold station techniques and test data for seismologists and others in the polar sciences community.

Under the current Cooperative Agreement, the funding mechanism for this work has been through annual or as needed supplemental proposals to OPP. Current funded capabilities include: 3.5 FTE; a pool of 40 cold-hardened broadband stations (currently deployed at POLENET and AGAP); a 60-channel seismic snow streamer; 100 quick-deploy boxes for summer-only stations; and a cold chamber capable of testing equipment for the extreme cold of the Antarctic Polar Plateau.

COMMUNICATIONS

Work under MRI awards for the International Polar Year (IPY) and Greenland Ice Sheet Monitoring Network (GLISN) as well as support from the core PASSCAL program has included development of Iridium-based communications interfaces with cold-rated equipment that allows for several levels of remote interaction. At the simplest, lowest-power end, network operations centers can receive state-of-health information and data snippets, and process command-and-control functions. At the other extreme, we are working with Xeos Technologies to expand the Iridium system to incorporate real-time data flow in addition to simple data transfers. Communications in high latitudes is evolving, and PSS technical staff will keep current on new developments in this area to ensure return of as much data as possible from these remote stations.

GREENLAND ICE SHEET MONITORING NETWORK

In 2009, IRIS was awarded $1.9M in MRI funding from NSF for the three-year development of GLISN. The development effort is a coordinated international collaboration for a new broadband seismic capability for Greenland. Initially, this was a partnership of eight nations—Denmark, Canada, Germany, Italy, Japan, Norway, Switzerland, and the United States, but Poland has since added on as a contributing nation and France is looking to contribute a new station as well. GLISN will contribute to our understanding of ice sheet dynamics by establishing a real-time sensor array of 25+ stations, including upgrading the performance of the scarce existing Greenland seismic infrastructure for detecting, locating, and characterizing glacial earthquakes and other cryoseismic phenomena. The development of the telemetry infrastructure linking the sites together into a coherent framework creates the temporal resolving capability and potential for rapid scientific response that can also be applied to other, future seismological efforts in other remote areas of the world. All data from GLISN are and will continue to be freely and openly available.

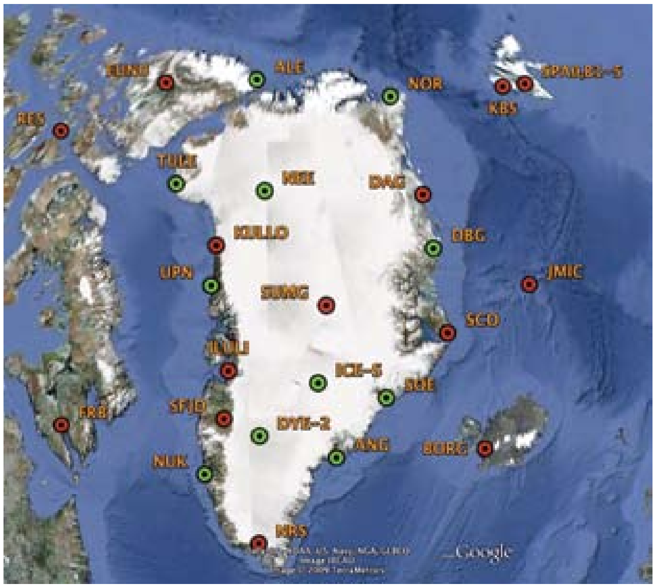


Figure A7.5. Map of GLISN.

Engineering and technical work by the PSS field engineering staff for GLISN is focused on: (1) upgrading equipment and adding real-time telemetry to existing seismic infrastructure in Greenland; (2) installing new, telemetered, broadband seismic stations on Greenland's perimeter and ice sheet; (3) coalescing telemetry from existing real-time, high-quality, broadband stations in and around Greenland into the GLISN network; and (4) distributing the real-time data to users and international data centers. In collaboration with GLISN, the Global Centroid Moment Tensor Project at Lamont-Doherty Earth Observatory will provide a near-real-time catalog of glacial earthquakes. The development incorporates state-of-the-art broadband seismometers and data acquisition, Iridium and local Internet, power systems capable of autonomous operation throughout the polar year, and stable, well- coupled installations on bedrock and the ice sheet. GPS will also be installed at sites on the ice sheet.

Oversight of the GLISN effort is provided on the U.S. side by the IRIS GLISN Science Advisory Committee (SAC) and includes as observers management and technical personnel from the PSS. The chair of the GLISN SAC as well as the GLISN Project Manager participate in the international GLISN steering committee to coordinate the NSF-funded GLISN effort with those of our international collaborators.

Due to the efforts of PSS, we were able to assure successes in the GLISN proposal and share our capabilities with our international partners

ACHIEVEMENTS

The polar seismology community has greatly benefited from the recent focused efforts of PSS. With OPP's investments in improving the designs of remote autonomous observatories and the procurement of cold-hardened equipment pools using the design efforts from this work, along with enhanced field support, we have achieved year-round recording for autonomous broadband seismic stations on the Polar Plateau, with data returns of over 90% (about the same or better than our fair-weather experiments). At the same time, we have minimized logistics support obligations to NSF by keeping designs small and light. Maintaining the existing capabilities and building on the progress achieved will require a sustained funding environment and a coordinated effort with the user community through the Polar Network Science Committee (a joint IRIS/UNAVCO advisory committee populated by polar PIs who provide guidance on required polar network capabilities).

NEW OPPORTUNITIES AND DIRECTIONS

To date, funding scenarios for the support of this facility have been on a year-to-year basis, depending on the scope of successfully funded annual OPP awards. Equipment resources are procured through yearly supplemental funding requests, based on funded projects for that year. Timing of these requests generally allows very little time to acquire, fabricate, test, and ship prior to the deployment to the field—sometimes as little as one week. With such specialized equipment working in areas of very expensive logistics and so little turn-around time, there is a risk that robustness of equipment rushed out the door cannot be assured. PSS has been successful in this "reactive" mode of funding, but risks the loss of staffing expertise in the long term without some assurance of continuous support. In addition, as the equipment in the pool begins to age (we are suspecting that the harsh environments for these installations will take a higher-than-normal toll on the instrumentation), we will need to replenish and, if possible, grow the pool to keep up experiments instrumented with the most robust systems possible. To ensure that specialized staffing can be retained to support these new capabilities at state of the art, continue the successes realized by OPP on the IPY seismic experiments, and protect the investment made to establish this polar-specific facility, we request a base level of funding to IRIS aligned with the IRIS core program Cooperative Agreements.

Beyond simply sustaining the new IRIS polar facility, there is exciting new equipment development for the PSS staff to pursue with NSF support. These new directions will further push the bounds of the polar environments in which we can record high-quality broadband seismic data. The following sections describe the sustainment and growth potentials proposed for the IRIS polar facility.

SUSTAINING SPECIALIZED POLAR SUPPORT CAPABILITIES

Personnel

A dedicated and well-trained staff that can focus on the unique requirements of polar experiments is critical to maintaining IRIS's support activities and to sustaining the investments NSF made on enhanced services during the IPY. IRIS has devoted personnel at the PIC and currently has 4.5 FTEs in PSS (3.5 directly funded by OPP and one funded under GLISN). Having dedicated PSS FTEs allowed IRIS to transform the 2008/09 field-season experiments by reducing logistics requirements and increasing data returns. Until now, this established polar support has been ephemeral in that retention of the 3.5 OPP-funded FTEs depended on yearly supplements; this way of funding FTEs creates the perception of an insecure job and makes it difficult to keep qualified staff. The GLISN position is funded only through September 2012. IRIS cannot maintain the levels of excellence currently represented in PSS without stable funding. An example of the benefits of a trained and stable polar staff was our ability to respond to the recent increase in polar climate research. Although specialized equipment for this kind of fieldwork requires development and planning in the time frame of years, because we had core PSS staff, IRIS was able to quickly provide a working solution for these challenging deployments. We are requesting that this Cooperative Agreement fund staff throughout the length of the award (synchronized with the IRIS core funding) and assume the cost of retaining the GLISN staff after that MRI award ends.

Equipment

To maintain an innovative polar station pool, IRIS will continue to pursue incremental development and modifications to the existing station, communications, and power-system designs. Battery technologies are continually evolving and will likely realize a surge in design innovation over the next several years. Although the station power system design is effective and compact, its cost is high. Having knowledgeable staff to monitor battery development, to design new systems, and to test emerging battery technologies for cold weather applications will be essential to ensure the most cost-effective solution is maintained. Like battery technologies, high-latitude communications are quickly evolving. The current polar station design has a solution for state-of-health communications, but the science community continually stresses the need for a real-time, full-bandwidth solution (currently unavailable). With better communications and advanced battery technologies, we could truly approach an infrequently visited, autonomous station, thus reducing long-term logistics costs.

The current pool of polar equipment is allocated through 2012–2013 Antarctic field season. As such, we cannot sustain further field requests without a responsive supplemental proposal to OPP based on current-year funded experiments. As mentioned above, in a reactive mode, robust designs are difficult to procure, fabricate, and deploy in an extremely abbreviated time frame, and as such, the benefits we have gained from the development work cannot be assured. In addition, due to the harsh environments, the equipment that

Figure A7.6. The work of the Polar Support Services engineers have allowed for vast improvements in low-power cold-rated, robust, super-insolated seismic systems for deployments in the some of the harshest polar environments. All designs are available at http://www.passcal.nmt.edu/content/polar-design-drawing currently constitutes the pool deteriorates at a higher rate relative to other instruments. Therefore, we are requesting basal sustainment funds for the polar pool that will permit continuation of the pool at its current deployment rate as well as allow for moderate growth to be responsive to the growing interest in climate-related monitoring in polar environments.

BACKBONE STATION HARDENING FOR POLENET AND AGAP

There is scientific interest in establishing a core reference network for Antarctica for long-term observations. A logical starting point for this network would be based on a subset of stations from the AGAP and POLENET experiments, but both of these experiments were designed and deployed as temporary installations. For long-term operation, station hardening will be required. PSS can leverage knowledge gained during the development MRI and GLISN projects to design and modify these stations to increase longevity and minimize logistics support requirements. Station modifications will most likely include a rugged metal station, a semi-permanent seismometer vault, upgraded communications, and an enhanced power system.

COLD, WET STATION PACKAGE

OPP has funded more than 15 glaciology projects with a seismology component. With the establishment of GLISN and the heightened interest in monitoring rapid glacial change, we expect that the number of proposals to perform higher-resolution experiments on the Greenland glacier systems and in other high-latitude environments will increase. These projects have proposed using short-period or broadband seismometers in environments with a high probability of flooding in the summer months, while still requiring extreme cold-hardening for winter operations. Flooding due to high surface melt rates poses challenges for both surface and borehole sensor installations. IRIS now has several prototype waterproof borehole instruments acquired with supplemental funding from OPP, but we currently lack waterproof short-period seismometers and digital recorders. Supporting these projects has required compromises in experiment design and high risks to existing instrumentation. To better support projects in these extremely wet ice-sheet environments, IRIS needs to pursue the development of a waterproof, quick-deploy seismic station. In addition to being waterproof, IRIS is working with manufacturers to test a borehole sensor with high tilt tolerance for recording in the dynamic glacial environment. This effort is in the early development phase, but stable polar staffing is required to continue progress and to provide the specialized support for these experiments.

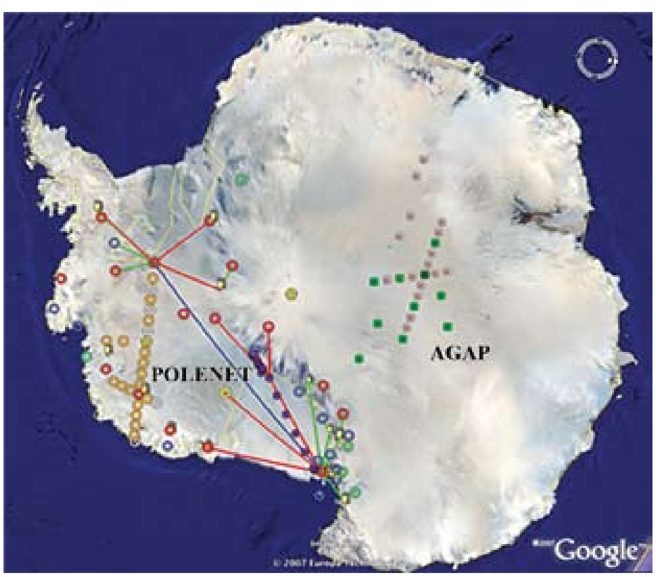


Figure A7.7. Map of POLENET and AGAP stations.


Figure A7.8. Meltwater river near the margin of the inland ice. Illulisat, Greenland (photo courtesy of Geological Survey of Denmark and Greenland).

ANTARCTIC FIELD SUPPORT FACILITY

Support of Antarctic experiments could be enhanced, while minimizing logistics costs, by establishing an observatory support facility at McMurdo station. This concept has been supported on an interim basis through funding of temporary projects, and has proven to be beneficial to the support of Antarctic field efforts. With no long-term funding assured, however, the on-ice support cannot be optimized. These on-ice concepts include:

- Establishment of a cold test site in McMurdo. Although an OPP-funded cold chamber is installed at the PIC, testing of fully integrated systems requires long-term runs in field conditions. McMurdo is ideal for this purpose because of its year-round Internet access. Little or no support would be required from Raytheon, other that IT support for communications links. This concept was introduced as part of the development MRI and it proved to be very valuable in the over-winter testing of system enhancements in actual field conditions.

- Establishment of a storage depot in McMurdo to store polar-specific equipment between seasons, reducing shipping cost and logistics. Current usage of a milvan is viewed as a temporary solution by Raytheon and requires yearly requests to maintain.
- Establishment of a small amount of dedicated lab space in McMurdo for test and computer equipment. The current use of Crary Lab loading docks is workable, but not ideal, particularly with the increased size of recent seismic and geodetic experiments.

It would be helpful to explore possibilities for a future dedicated geophysics facility that would provide the appropriate space for storing, staging, and supporting seismic, geodetic, and other geophysical experiments supported in part by IRIS and UNAVCO. An example of an existing building that would provide the necessary space is the Berg Field Center. The size and layout make it ideal for staging large geophysical experiments and the proximity to the future science cargo center in the expanded science support complex will reduce the logistics involved in getting the equipment prepared for field deployments.

Figure A7.9. IRIS (center) and UNAVCO (left) cold station development testbeds overlooking McMurdo Station, Antarctica. These testbeds were used to proof MRI designs in field conditions in Antarctica (photo by T Parker).