Report on the 2014 IRIS Workshop, "Multiuse Facilities for Multiuse Data for Science & Education"

1. Introduction

The goals of the first of three community-wide workshops under the SAGE Cooperative Agreement were to: (1) review the newest developments in seismology, (2) set strategic priorities for facilities operations and new initiatives under the new Cooperative Agreement, and (3) explore future scientific opportunities that might be supported by new facility capabilities and services, especially post-2018. The context for the Workshop included a variety of science planning documents from the IRIS community and other geoscience communities in closely related fields, including the Seismological Grand Challenges report, the National Research Council report on New Research Opportunities in the Earth Sciences (NROES), and the EarthScope Science Plan.

Seismological research addresses both fundamental problems in understanding how the Earth system works including earthquake processes and global Earth structure and dynamics, as well as important societal problems such as natural hazards, energy resources, environmental changes, and national security. Over the past few years SAGE facilities have supported research that has led to exciting new discoveries in ambient noise tomography and its use, episodic tremor and slip, induced seismicity, teleseismically-triggered earthquakes, and the movement and calving of glaciers. Increasingly, the problems seismologists are addressing demand multidisciplinary and interdisciplinary approaches involving geodesy, mineral physics, geochemistry, geodynamics, magnetotellurics and marine geophysics. The applications of seismology are also rapidly expanding into new fields in the ocean, atmospheric, and polar sciences. These changes were reflected in the organization and discussions at the 2014 IRIS Workshop.

Technological progress in a wide range of areas is also facilitating new modes of seismological research and discovery. These include advances in batteries, sensor technology and packaging, and communications that enable deployment of seismometers on land in very large numbers not feasible just a few years ago, as well as observations in very remote and hostile environments such as the polar regions. At the same time, advances in ocean engineering are on the threshold of making continuous real-time seismological observations in the oceans feasible and affordable. Finally, advances in high performance computing are enabling simulation of seismic wave propagation to teleseismic distances at all observable frequencies enabling full waveform tomographic inversions.

One fundamental underlying principle of IRIS-operated facilities is the integration of research and education. In its report on "Status for the Geoscience Workforce 2014", the American Geological Institute projects a shortage of around 135,000 geoscientists by the end of the decade. The expected shortfall arises partly from the demographics of Earth scientists in the petroleum industry, with a large proportion nearing retirement. Also, a large increase in demand for Earth scientists with strong quantitative skills is expected as a result of growth in industries related to near-surface geophysics, including groundwater, and wastewater injection. This workforce will be most effectively developed through a strong education program based on integration of research and education for both undergraduate and graduate students.

The agenda for the 2014 IRIS Workshop reflected the importance of broad community participation in advance planning for facilities in light of the recompetition of the management and operation of the SAGE and GAGE seismic and geodetic facilities at the end of the current Cooperative Agreements. The geophysical community has benefitted from sustained participation in governance of such facilities since the beginning of IRIS's first Cooperative Agreement with NSF nearly 30 years ago and it is very important that the community provide input to NSF on its future facility needs and how those facilities should be managed post-2018. This workshop report is envisioned as one of many mechanisms for the IRIS community to provide input to NSF on this topic.

2. Scientific Advances and Future Directions

2.1 Common Themes

IRIS Workshops have always been distinguished from typical science conferences by a focus on the role of seismological facilities and services in supporting seismological and other geoscience research. Nevertheless, the plenary sessions during the 2014 Workshop were notable for being organized around scientific themes rather than services, and encouraging presenters to set the stage for discussion about facility capabilities needed in the future to address the most important scientific questions. The themes that emerged from this process included:

- The expanding use of seismic data in research areas other than the study of deep Earth structure and processes;
- The increasing importance of seismology in the oceans, including both broadband seafloor instruments and hydrophones deployed in large numbers on floats;
- Strong interest in the development and use of new observational systems, such as Large N, in part by working more closely with service companies in the exploration industry;
- The importance of cyberinfrastructure, including High Performance Computing (HPC), better tools for joint use of data from different disciplines (*e.g.* seismic, geodetic, and geoelectric), better management and re-use of Earth models, and better support for community software, especially for handling large waveform datasets.

2.2.1 Science Challenges Plenary Session

The opening plenary session introduced the *Science Challenges* committees established recently by the IRIS Board of Directors.

Presentations from the committee on *Thermo-Chemical Internal Dynamics and Volatile Distribution* illustrated how large-scale observational networks, such as USArray, analogous projects on other continents (*e.g.* EPOS), and experiments such as PLUME, are advancing seismic imaging into the realm of meaningful comparison with geodynamic modeling as well as resolving lithospheric processes such as delamination. The presentations demonstrated the importance of dense, wide aperture arrays to image structure in the lower mantle and the need to extract more information from seismic waveforms through use of more advanced computing capabilities. Key future research directions include improving seismic images using full waveform analysis, improving interpretation of seismic images through development of new interdiscplinary models, and expanding instrumental coverage in the oceans.

Presentations from the committee on *Faulting and Deformation Processes* illustrated that we continue to encounter important complexity on smaller spatial scales than can be resolved with current data and modeling methods, but that at least some of this complexity can be resolved with anticipated improvements in observing systems, better integration of data from different disciplines (seismic, geodetic, laboratory), improvements in modeling techniques, and by taking advantage of phenomena such as induced earthquakes as inadvertent large-scale *in situ* experiments in the physics of rock friction and rupture. Key future facility needs identified in these presentations included dense, high-resolution seismic and GPS networks of various apertures, offshore observations at subduction zones (seismic and geodetic), and improved and expanded rapid response capabilities.

Presentations from the committee on *Change and Interactions among Climate, Hydrology, Surface Processes, and Tectonics* illustrated that contributions from seismology may be essential to making progress in addressing forefront questions in other disciplines of Earth science, such as the interaction between climate and mountain building and the contribution of basal heat flow to ice sheet and ice shelf dynamics. Particularly exciting new research opportunities were seen in cryospheric studies of heat flux at the base of ice sheets in Greenland and Antarctica, in studying ice sheet/ocean interactions, and in understanding fault slip at the base of ice sheets. Key facility needs include expanding the pool of broadband instruments available for work in polar regions and improving the instrumentation to meet the unique challenges of operating in the polar environment.

2.2.2 Very Wide Aperture Arrays Plenary Session

This session highlighted the diverse disciplines that complement seismology and contribute to advances in understanding the dynamics of tectonic and earthquake processes. While the growing importance of multidisciplinary work is well recognized, these presentations illustrated that significant advances continue within disciplines and showed that enormous and only partly-predictable scientific returns continue to come from investment in the largest and most sophisticated geophysical observation systems that have been deployed.

Gary Egbert discussed recent advances using large two-dimensional arrays of magnetotelluric (MT) instruments and new analysis techniques to fully invert for impedance and vertical magnetic transfer functions. The large aperture of EarthScope magnetotelluric arrays allows resolution of lateral variations to greater depths – even beyond the lithosphere-asthenosphere boundary – and mapping of sutures that record assembly of the North American continent.

Joan Gomberg highlighted advances using high-rate geodetic data to address long-standing scientific questions about rupture duration versus seismic moment as well as applications in earthquake early warning.

Complementing these two presentations, Hitoshi Kawakatsu illustrated the investment necessary to collect comprehensive data, and showed that data from diverse seismological networks in Japan facilitate integration of tomography, migrated receiver functions, and earthquake centroid–moment tensors to resolve ambiguity that would arise if fewer data types were available.

Finally, Göran Ekström outlined the dedication and ongoing refinement of operations needed to achieve the exceptional quality of USArray data, and demonstrated that this effort has provided unique new research opportunities, such as studying wavefield polarization and attenuation on a continental scale across North America.

2.2.3 Dirt, Data, Desktop, Dissemination Plenary Session

This session was organized to discuss how integration of the various services from deploying instruments in the field to managing data and producing data products provided by IRIS facilities link together to support a research project, a concept sometimes referred to as "Dirt-to-Desktop".

Geoff Abers described collection of familiar types of data using facility programs, complemented by collection of new types of data by individual investigators to elucidate previously unknown Earth processes. In part, Abers concluded that some types of data first used scientifically in individual projects can prove so important that facilities should adopt the systematic collection of these new types of data to enhance quality control, better quantify uncertainty, and facilitate research in emerging new areas.

Emily Hooft described a study that significantly advanced mapping of volcanic magma bodies. She illustrated the use of instrumentation and data services to facilitate both the collection of new data and the re-use of data from studies completed decades ago. Through the innovative use of community-endorsed software Hooft was able to extract Earth structure information from the data beyond that typical for similar studies and produce visualization products that effectively conveyed her results to the general public.

Gary Pavlis reviewed the evolution of projects over his career, noting that facility services had reduced the time that he and his collaborators spent on work that had become standardized, thus giving them more time for genuinely innovative work and increasing the accomplishments from individual projects. Based on time still spent in his current projects on work that could be standardized, Pavlis concluded that it would be fruitful for Earth science facilities to extend their support for cyberinfrastructure, including:

- Services to facilitate re-use of code;
- Community software for handling large volumes of waveform data;
- Mechanisms for joint use of data from several disciplines;
- HPC sufficiently accessible that adjoint tomography and other computing-intensive tools are widely and routinely used; and
- Improved products that make evident what data were used, offer mechanisms to update products with new data, and are useful in further analysis such as tomography to compute travel times and synthetic waveforms.

This oral session included breakout groups for more in-depth discussion, with opportunities for input from more participants than is typical of a large plenary meeting. In the breakout groups, the participants strongly supported IRIS facilities continuing to provide "core capabilities", such as observational systems and data management services, while individual investigators at universities and research institutions continue to provide "content", *i.e.* ideas for specific projects and the original intellectual effort needed to successfully carry out projects and interpret the results.

Areas in need of more emphasis within the framework that IRIS provides include:

- Cyberinfrastructure including support for a community software environment for handling large volumes of waveform data including metadata, quality control metrics, and more generic solutions for graphical interaction with large datasets;
- A pool of instruments for rapid mobilization (such as in response to significant

earthquakes, earthquake swarms, volcanic eruptions) with equipment and deployment strategies that evolve with science targets; and

- Support for research related to geophysical hazards (such as strong motion systems and coupled GPS/seismic systems).

2.2.4 Unexpected Science Session Plenary Session

The four talks in the Unexpected Science session highlighted the breadth of new science being done with seismic data beyond the science of earthquakes. The presentation by René-Édouard Plessix of Shell described how the exploration industry is using new data acquisition systems together with HPC-based data processing and modeling to obtain high-resolution seismic images. Plessix explained that industry is pushing the envelope for HPC demands in these seismic imaging problems, and during discussion following his presentation it became clear that envisioned academic applications also require access to the most advanced HPC facilities to take full advantage of envisioned next-generation portable instrumentation.

Victor Tsai presented an overview of the remarkable range of new studies using the ambient noise seismic wavefield that, while mostly in the proof-of-concept stage, show promise at all scales:

- Locally, *e.g.* using data from the now well-known Long Beach array with 100m spacing;
- Continent-wide, *e.g.* using ambient noise across the Transportable Array together with H/V ratios of Rayleigh waves to constrain structure in the uppermost few kilometers of the crust;
- Globally, *e.g.* cross-correlating data from GSN stations to obtain core-sensitive waveforms.

These applications show significant scientific returns can be expected from recording and archiving continuous data during all types of deployments and from broad access to “big data” computing resources, such as those used for recent seismological research at Lawrence Livermore National Laboratory and Oak Ridge National Laboratory.

Using data from sensors at Transportable Array stations, Catherine de Groot-Hedlin discussed studies of atmospheric gravity waves. These waves arise in North America from tropospheric winds over the Rocky Mountains and from tornadoes, and are observed more often near the Great Lakes, perhaps because of better propagation. Strong spatial and temporal correlation between infrasonic gravity wave measurements and observations from the Atmospheric InfraRed Satellite (AIRS) provide mutual confirmation. While AIRS offers greater spatial resolution, the mutual benefits of interdisciplinary collaboration in facilities management is demonstrated by the time resolution of infrasound measurements compared to twice daily AIRS images.

Rick Aster concluded the session with a discussion of using seismic sensors to record a broad range of environmental signals, many of which are related to climate change. He highlighted work at the poles to study ice-related phenomena, including break-up of ice sheets and icebergs and various glaciological applications. He also reviewed recent work to study sediment transport, a topic also touched on by Victor Tsai. Understanding ice and fluvial dynamics through a period of changing climate has great societal import and extracting the signal from these processes from seismic nature will continue to be a growing front on the bounds of seismology.

3. Current Facility Capabilities and Future Needs

3.1 Current Facilities

The Foundational Facilities operated by IRIS as community-governed, multi-user facilities are indispensible for research and education in seismology and the Earth sciences as practiced today. Several of these instrumentation programs – especially GSN, PASSCAL, and OBSIP – share the dual challenges of aging instruments and need for recapitalization, with a demand from investigators for new technology that is more rugged, consumes less power, and enhances communications. Each facility, however, faces distinct needs to continue providing support for cutting-edge work.

3.1.1 The Global Seismographic Network (GSN)

The GSN, operated jointly by the NSF and the U.S. Geological Survey (USGS), comprises more than 150 high-performance permanent seismographic stations that provide data for global studies of earthquakes and deep Earth structure, earthquake and tsunami warning, and nuclear test ban verification. The GSN is a dual-use network, designed for both basic research and operational monitoring. In addition to NSF and the USGS, several other agencies of the Federal government (Commerce, Energy, Defense, and State), and other national governments, act as partners in the operation and maintenance of the GSN, offering a high return to the NSF for its investment.

A GSN station is characterized by the ultra-broadband response of the primary sensors, special site selection and installation to minimize background noise levels, very wide dynamic range of the combined sensing and recording system, and backup systems to ensure exceptionally high data availability. The stations are distributed around the world as uniformly as possible (with the exception of the deep sea floor) to facilitate studies of global Earth structure. Rigorous quality control and calibration procedures are employed to compile a long term archive of high quality seismic data that is needed for many types of studies, including those based on comparison of records from earthquakes tens of years apart.

Required periodic replacement of instrumentation and major work on site infrastructure (*e.g.* vaults) are not included in GSN annual operating budgets, leading to concern about the long-term viability of the network. Fortunately, over the past ten years, the NSF, USGS, Department of Energy, and Department of State have provided additional supplemental funding for the GSN, including support for new dataloggers and new borehole sensors. If similar opportunities for supplemental funding continue to arise in the future, and if operational funding for the network is maintained at sustainable levels, we can expect the GSN to continue to provide excellent quality data well into the future. A key issue for the future of the GSN is whether a significant effort and resources should be devoted toward extending the network into the oceans, establishing GSN sites on the deep sea floor.

3.1.2 Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL)

PASSCAL facilitates university-based temporary field deployments funded by the NSF and other agencies of the U.S. Government. Services to investigators include loans from a large pool of short period and broadband seismographs, geophones and magnetotelluric systems. The seismographic systems are used for temporary deployments of a few weeks to several years, at locations in the United States and around the world, utilizing both passive seismic and controlled-source seismic techniques.

All of the magnetotelluric systems and many of the seismographic systems in the pool were acquired about ten years ago under the USArray MREFC award to IRIS as part of NSF's EarthScope project. In addition, special funding from the DOE during 2001–2003 made it possible to replace selected components in the non-USArray part of the pool. However, presently the median age of instruments in the PASSCAL instrument pool is ~9 years and some instruments are over 20 years old. Recent technological advances have facilitated development of more robust systems (e.g. posthole broadband sensors; autonomous nodal sensors) and new approaches to data acquisition that are widely used outside of academia. A key challenge for PASSCAL is how to recapitalize its instrument pool with these newer, simpler and more robust sensors and sustain the level of support PASSCAL has traditionally provided to the community given the present highly constrained budget climate.

3.1.3 Transportable Array

The Transportable Array (TA) is a set of more than 400 broadband seismic sensors, recording, and telemetry systems that "rolled" east across the conterminous U.S. over the last ten years occupying nearly 1700 sites on a grid with ~70 km spacing. The TA has collected approximately ten years of continuous high-quality broadband seismic data which are made freely available to scientists and the public worldwide and continue to be used in a wide range of research and outreach activities. Objective metrics of TA data quality significantly exceed those of many permanent regional networks, offering unprecedented opportunities for quantitative investigation of wavefield polarization and amplitude, and facilitating advances in studying velocity and attenuation structure in the Earth. In 2013 the TA began relocating to Alaska. The initial SAGE plan to redeploy the TA in Alaska included ~300 instruments with a grid spacing of 85 km but funding reductions have necessitated a descoping of that plan. Innovative new sensor and battery systems are being developed to meet the logistical and technical challenges of operating in Alaska. For example, at many sites new posthole sensors will be emplaced in shallow boreholes, rather than the surface vaults used in the lower-48 TA deployment. The TA will be fully deployed in Alaska by 2018.

3.1.4 Central and Eastern United States Seismic Network (CEUSN)

The NSF, USGS, Nuclear Regulatory Commission, and Department of Energy recognized the unique opportunity to retain selected Transportable Array seismic stations in the Central and Eastern United States beyond the standard TA deployment of two years. An inter-agency working group identified ~160 TA stations for long-term operation as part of a CEUSN based on consideration of multiple criteria. Outside of regions with existing permanent seismic networks sufficient for the current needs of broader society, CEUSN stations were chosen to maintain a nearly uniform backbone while addressing specific needs that include good coverage in regions of higher seismic hazard, in the vicinity nuclear power plants and other critical facilities, and at potential scientific targets. Each selected station is transitioned shortly before its planned removal as part of the TA project, and completion of the entire 160 station CEUSN is planned by 2018. At that point the USGS Earthquake Hazards Program will take over operational responsibility for the CEUSN.

3.1.5 Polar Support Services

Typically, 5% to 10% of the experiments supported each year by PASSCAL are in polar regions, mostly Antarctica, Greenland, and Alaska. Polar projects commonly require a level of support that is several times that of seismic experiments in less demanding environments. A new field of glacial seismology is emerging from these experiments including studies of tidally modulated slow slip events on the Whillans Ice Stream, coda waves produced by atmospherically-forced shallow icequakes at Mount Erebus, icequakes triggered in the Antarctic ice sheet by teleseismic Rayleigh waves, transoceanic destabilization of calving fronts and generation of mega-icebergs by tsunamis, smooth tidal modulation of ice shelf flow, and repeating and chaotic transitions in glacial slip patches. Deploying at near-to-source distances oven provides critical information to discriminate between competing source models – more so than simply larger numbers of distant stations.

In order to ensure polar projects a high level of success commensurate with NSF's investment, IRIS established Polar Support Services and is funded by NSF's Polar Programs Division to support new and ongoing experiments in Antarctica. IRIS Polar Support Services has established a pool of sensors, ancillary equipment, and specialized station enclosures for use in cold environments and developed successful cold station deployment strategies. Support for UPPA-GL, RRISWIV, POLENET, and GLISN are important parts of work by IRIS' Polar Support Services. Challenges remain to test and vet equipment as it arrives in a polar environment to field more efficiently, to provide timely and cost effective training, to offer easily reachable expert troubleshooting and aid with instrument performance, and data QC, backup and archiving.

3.1.6 Ocean Bottom Seismometer Instrument Pool

NSF established OBSIP in 1999 as an instrument facility to support research and further our understanding of marine geology, seismology, and geodynamics. OBSIP is comprised of a Management Office operated by IRIS and three Institutional Instrument Contributors – Lamont Doherty Earth Observatory (LDEO), Scripps Institution of Oceanography (SIO), and Woods Hole Oceanographic Institution (WHOI) – each of which contribute both instruments and technical support to the pool. Ocean bottom seismometers available through OBSIP include 160 broadband instruments for long-term deployment of passive experiments and 93 short period instruments that are used for active seismic refraction studies in coordination with vessels towing airgun arrays.

Addressing many of the seismological grand challenges will require increased use of OBSs, which will be possible only with a larger community of individual investigators, necessitating a lowering of barriers to entry through educational efforts (webinars, short courses, etc.,) in techniques necessary and specific to using OBS data. Improved instruments for use on the continental shelf and in subduction zones are a priority. Other development needs for OBSs include more accurate clocks, better noise reduction, and improved horizontal sensors with known orientation. Sensor types of interest to biological and physical oceanography communities could leverage availability of the power, data acquisition, and timing systems on the OBS platform, but greater cost-effectiveness through such multidisciplinary platforms may be limited by the necessity of placing some sensor types high in the water column.

3.1.7 Amphibious Array Facility (AAF)

During 2009, NSF's Ocean Sciences Division funded the construction of an Amphibious Array Facility of 60 Ocean Bottom Seismometers by the three Instrument Centers of the OBSIP. The first deployment of the AAF was for the Cascadia Initiative, where the OBSs are utilized in four one-year deployments that provide an offshore extension of the EarthScope Transportable Array, as well as three dense experiments focused on either imaging various properties of the thrust interface and forearc or recording local seismicity. The scale of the Cascadia Initiative reduced the costs per instrument-year of data compared with earlier PI-driven experiments. Hundreds of scientists have already accessed the data, and interesting results are already being published. A workshop will be held in October 2014 to evaluate the Cascadia Initiative after 3 of 4 years of planned deployments; make recommendations for the type, size and scope of future scientific studies using the AAF; and identify critical scientific targets given the capabilities of the Array.

3.1.8 Global Reporting Observatories – Chile (GRO-Chile)

GRO-Chile is a collaborative project between the University of Chile and IRIS established a network of 10 geophysical observatories with combined broadband seismic, strong motion, infrasound, and meteorological sensors spaced at 300 km along the length of Chile. Data are openly available in near real time. Data coverage beyond these initial 10 stations will be increased in this region tremendously by an additional 65 high quality broadband seismic stations installed by the University of Chile which will help bolster research as well as improve the tsunami early warning detection system coverage.

3.1.9 Data Services (DS)

DS includes collection, curation, and open distribution of data from all IRIS-managed observational systems and extensive collections of seismic data contributed by others. The transition to near-real-time delivery of data from nearly all permanently installed stations has enabled large increases in efficiency of data collection and handling. Advances in information technology, and corresponding decreases in cost of storage, have made it possible to manage a rapidly growing volume of seismic data without comparable increases in spending on new storage media. Nearly continual development of new data distribution mechanisms to take advantage of broader technological advances, in particular web services, has made it possible for researchers to work more efficiently with ever-growing volumes of data. Recently introduced services include expanded data quality analysis, services delivering a wider variety of data products, and full capability auxiliary data centers for data collection, storage, and distribution.

Planning for instrument development to support "Large N"-style deployments must be accompanied by planning for how to manage and distribute the anticipated huge data volumes whether these data are stored locally or in the "cloud". The vastly larger data volumes present data management, processing and visualization challenges for science users. For example, seismologists who continue to download data to their local systems will require new, more efficient distribution and formatting tools. At the same time, researchers who adopt use of community high performance computing systems will require new types of support to facilitate efficient data availability on compute nodes.

3.1.10 Education and Public Outreach (EPO)

EPO leads and coordinates IRIS education and outreach activities for public audiences from grade 5 to adult, teachers, undergraduate and graduate students, and faculty within the Earth sciences. EPO activities include an undergraduate summer internship program, professional development experiences for teachers and college faculty, training for graduate students, seismographs in schools and related collection and use of seismic data, Teachable Moment presentations after major earthquakes, public and educational displays, IRIS/SSA distinguished lecturers, publications including videos, animations, online recordings, and classroom modules, and the dissemination of materials, activities, software and data via the IRIS website. EPO coordinates its activities nationally and internationally with those of other organizations to leverage impact.

Growing demand on EPO arise from the predicted shortfall of Earth scientists in the US workforce projected by AGI, the scarcity of students with strong quantitative skills who express interest in Earth science, and budgetary limitations at publicly-funded universities. As a result, early career investigators/educators look to EPO to address its education mission through improved and expanded services. Their suggestions include a community shared repository for lectures, student exercises, and other educational modules, expanded webinar series and short courses, improvements to a repository for community generated software, systematic compilation of information about career opportunities beyond academia, and additional features in data access tools and wizards, with a focus on access via mobile devices.

3.2 Foundational Facilities: Five to Ten Year Outlook

Over the next five to ten years, state of the art research in seismology and allied Earth Science disciplines using seismological data requires capabilities and services described in this section.

3.2.1 Full Wavefield Sampling by Dense Sensor Arrays – "Large N"

Resolution of near-surface, crustal, and lithospheric Earth structure has been fundamentally limited by an aliased wavefield. Expense and logistical difficulties associated with deploying and maintaining broadband stations have generally limited passive recording experiments to fewer than 100 sensors. Some controlled-source experiments, such as the recent Salton Sea experiment, have included recording at several thousand sites, but this exceeds the capability of PASSCAL to support routinely and the investigator community to deploy with current systems. Imaging experiments at multiple scales ranging from mantle anisotropy to whole-crust structure to mapping of near-surface faults and hydrologic features, analysis of attenuation and imaging of crustal anisotropy clearly would benefit from access to many more sensors.

Technical solutions exist to deploy enough systems, at least for imaging at frequencies greater than 1 Hz and particularly as geophysical exploration technology is evolving. But there are not enough sensors or digitizers packages currently available to the academic community for comparable work, particularly at frequencies less than 1 Hz and for three-component sensors of any frequency range. Increased memory, on-board GPS timing, and a better power system would enable sensor/digitizer packages to be deployed for longer periods of time, requiring fewer maintenance trips (which would decrease logistical challenges and expenses) and significantly increase the uptime and amount of data recorded from each site. Along with a new generation of field hardware, there needs to be development of software and procedures for handling much larger datasets (see 3.2.3).

3.2.2 High Performance Computing for Earth Science

Transformative science using seismological data will require dedicated resources to fully leverage new computational capabilities to take advantage of the growing data volumes, computationally demanding methods of simulating elastic wave propagation, and studies of coupled dynamical systems operating at different scales. Seismologists have participated in creation of many of the computational building blocks needed to transform the way that solid Earth system science is done. A national commitment to develop exascale computing will lead to creation of advanced computing facilities. But, on the cusp of a transformation, Earth scientists face hurdles that include lack of sufficient and sustained access to leadership-class computing, difficulty sustaining intensive collaborations between Earth scientists and computational scientists for continuous development of next generation tools, and support services for community-wide use of simulations and inversions requiring mesoscale computational resources. Thus, there is a need to establish and sustain strong connections between Earth scientists and developers and operators computing facilities. Teams of software engineers and computational scientists are needed to commit sustained effort to address the distinct requirements of Earth science research.

3.2.3 Cyberinfrastructure

With the expected development of Large N and the collection of large volumes of waveform data from thousands of instruments deployed for individual experiments, advances in cyberinfrastructure will be needed to efficiently manage these large data volumes at the PI level, including support for a community software environment for handling large volumes of waveform data including metadata, quality control metrics, and more generic solutions for graphical interaction with large datasets. Demand for more sophisticated data products and other new services involving integration of data from different disciplines is expected with the growing importance of multidisciplinary research to address grand challenges science questions. Participation in EarthCube and similar geoscience-wide cyberinfrastructure initiatives is essential.

3.2.4 Rapid Array Mobilization Pool (RAMP)

Rapid deployments are required for scientific objectives (*e.g.* to record early aftershocks following larger earthquakes to improve our understanding of rock fracture and friction) and to meet the needs of broader society. Broader society benefits from rapid deployments could include aftershock early warning for rescue and recovery efforts and prediction of volcanic eruptions. A modern RAMP pool, with 100 or more instruments, could also contribute to capturing environmental phenomena such as floods and dam release events (i.e. fluvial seismology).

Sensor capabilities to meet scientific needs include short period seismic, geodetic, infrasonic, geochemical, and photogrammetric systems, real-time telemetry, ideally based on a self-organizing network, and automatic registration of metadata that are typically required in a rapid mobilization scenario. The replacement costs for the existing RAMP instruments are great enough to inhibit deployment in situations with a high risk of loss during times of elevated natural hazard risk or in urban situations where vandalism and accidental damage are likely. A modernized RAMP capability designed to address these shortcomings is a high priority.

3.2.5 Ocean Observations

The need for seismic data from oceanic regions is obvious in several ways, including the large fraction of the Earth's surface covered by oceans and the poor resolution of global tomographic models in the southern hemisphere where oceans are more predominant. There are several parallel developments leading towards data collection strategies that avoid the budgetary and technical challenges of permanent seismic stations in the oceans.

- ADDOSS or Wave Glider is an autonomous vehicle at the surface that can be used as a communications gateway with an OBS, and even to autonomously launch an OBS at lower cost and less ship time than is typical today. Acoustic modems allow continuous telemetry of 1 Hz data and retrieval of 50 Hz data segments with a latency of a few minutes.
- Long-deployment OBS. Development of very low power dataloggers, atomic clocks with much smaller drift rates and advances in battery technology will make OBS deployments of 2-3 years feasible in the near future significantly reducing present deployment and recovery costs.
- Mermaids are hydrophones attached to a few of the thousands of Argo floats deployed for oceanographers to measure temperature and salinity. They record P from moderately large teleseismic earthquakes (magnitude greater than 6.0 to 6.5, depending on noise conditions) and from local events to magnitude 2. Despite not recording S, Mermaids can provide a lower cost alternative to temporary OBSs for some types of studies, such as mantle plume tomography. If deployed in a dense array, they can determine relative locations by exchanging chirp signals, and surface occasionally to transmit data and obtain an absolute location by GPS.
- "Son-O-Mermaid" is a string of hydrophones hung from a buoy, which has an Iridium receiver/transmitter for near-real-time data telemetry and command-and-control. Location is known continuously from a GPS receiver on the buoy. Wave-heave energy harvesting is in development, which could provide sufficient power for a full-ocean depth fathometer, a dual-frequency GPS to enable tsunami detection, and payload for other scientific applications.

3.2.6 Environmental Monitoring at GSN Stations

The GSN is an official observing system within the Global Earth Observing System of Systems (GEOSS), an international program to realize a future wherein decisions and actions, for the benefit of humankind, are informed by coordinated, comprehensive and sustained Earth observations and information. While many elements of the GEOSS work program relate satellite data, the program also aims to coordinate the collection and open sharing of in-situ data. The power, timing, and communications systems at protected and sometimes difficult to access sites of GSN stations offer an opportunity to leverage the infrastructure investments for more benefits to broader society. Installation of meteorological and infrasonic sensors at TA stations in the conterminous US and interest in a variety of environmental sensors at TA stations in Alaska has demonstrated benefits that can be achieved.

3.3 Frontier Facilities: Five to Ten Year Outlook

3.3.1 Subduction Zone Observatory (SZO)

SZO is envisioned as an integrated, interdisciplinary approach to understanding subduction zone processes. SZO research will have enormous societal relevance, given the population centers all along the coast that are subject to earthquake, tsunami, and volcano hazard. Existing geophysical networks and observatories – including PBO, COCONet, GRO-Chile, the Cascadia Initiative, and TA stations in Alaska – will provide key infrastructure to start the SZO's backbone. SZO will grow through infill with strategic deployments of broadband seismometers, high-sample-rate GPS, and other types of sensor systems. Small, flexible projects led by individual investigators can be designed and performed within this larger framework.

There was enthusiasm for this concept both at the AGU 2013 Annual Fall Meeting and at the 2014 IRIS Workshop. During the SZO SIG meeting, numerous community members contributed their ideas regarding a SZO. Overall, three themes are emerging as core concepts for SZO. First, the community is enthusiastic to cover a broad suite of scientific targets and a large range of geographic locations. Hence, at this relatively early stage of developing the SZO concept, a wide range of scientists can see opportunities for progress that they are interested in. Second, SZO needs to be a multidisciplinary scientific effort involving not just seismologists and geodesists, but also geologists, volcanologists, geochemists, and geodynamicists. Third, there is a need for international participation throughout all stages of SZO, including the earliest planning and prioritization of science goals.

3.3.2 Global Array of Broadband Arrays (GABBA)

Global Seismology continues to advance steadily using well-established global and regional seismographic networks. Valuable and unique observations of earthquake processes will continue to be harvested from these facilities for many years to come, as will additional constraints on the seismic properties of Earth's interior. But while global models derived by different groups show growing congruence of major features, including zonation of the spectral characteristics of the mantle, this is not true of shorter wavelength structures.

Because there is a dichotomy in the spectrum of mantle heterogeneity and the long wavelength anomalies, we have an opportunity for targeted use of a finer tool to significantly sample the short wavelength features of deep Earth structures by deploying intermediate-term seismic arrays at strategically selected sites around the world. Expanding fundamental seismological observations from ground motion at isolated points on the globe to large-aperture, broadband observations of ground motion, ground-motion gradients, and wavefield slowness would transform investigations of the dynamics of the Earth's deep interior, while also greatly increasing the information available to explore earthquake ruptures.

3.4 Enhanced Support for Human Resources

A core message from the Workshop was the need for enhanced support for human resources, including individual investigator and multi-investigator projects, graduate education, and professional staff. At a minimum, the need for human resources would justify growing the existing IRIS intern program to several times its existing capacity. There are a variety of additional activities that IRIS should consider, at least at the level of pilot programs, for the development of human resources.

- Code Re-use Support, for programs written by graduate students.
- Undergraduate Course Depository, with contributed materials that are shared within a small group until ready for wider distribution.
- USArray Short Course Materials, extended into a stand-alone graduate-level course, including research skill-building activities.
- Video Lectures, targeted at graduate students on specific topics where there may not be any local faculty members with that expertise.
- Mid-Career Short Courses, highlighting new techniques.

- Quantitative Videos and Animations, to attract more physics and math students.
- Physics and Math Classes and Textbooks could be encouraged to use more examples from seismology and geophysics.

4. Conclusions

The predominant theme emerging from the 2014 IRIS Workshop is that major progress in understanding Earth dynamics can be facilitated in part by technological advances, including use of new observational sensors and systems, and in part by improved cyberinfrastructure, such as more extensive use of reliable community software and more accessibility to HPC for analysis and modeling of extremely large datasets. Complementing these enabling technologies is an increasing demand for services that support seismology in the oceans and polar regions, and the expanded use of seismic data in research areas other than the study of deep Earth processes.

Researchers and educators in seismology and related disciplines continue making full use of all of the facilities currently managed by IRIS, often in new and innovative ways. At the same time, the research community described how new facilities are required on a short time scale – five to ten years – to lay a foundation for taking full advantage of many new opportunities and to make significant further advances at the frontiers of geoscience research.

A range of next steps are required to implement the envisioned advances, including collection of white papers on new science facility concepts. There are numerous venues at which IRIS should organize or contribute to activities that focus on services beyond the SAGE Cooperative Agreement, including workshops specific to particular areas, community strategic planning activities that extend across the geoscience research community, and meetings of IRIS committees. The designs needed for some of the new services could be clarified by several pilot projects, such as in HPC, ocean seismology observing systems, global arrays for broadband seismology, and large portable arrays of independent nodal seismic systems.

We are fortunate to be working in a time when the possibilities for important advances are both apparent and so numerous that they foster ambitions that exceed even what would be possible with very generous resources. Our ongoing dual challenges are to prioritize the services that can most effectively advance our science in today's constrained funding environment and to articulate the benefits from our research sufficiently well to secure additional resources from both traditional and non-traditional sources in the future.

5. Appendix

Workshop Program: A PDF of the 36-page program book is posted on the IRIS web site at http://www.iris.edu/hq/publications/meeting_materials. The program includes descriptions of all of the SIG meetings, abstracts for all of the plenary session presentations, a list of posters presented at the Workshop, and a list of Workshop participants.

Plenary Sessions: Material for all of the presentations during plenary sessions is posted at http://www.iris.edu/hq/meetings/2014/06/iris_workshop_sunriver_oregon/plenary. This material includes abstracts, except for presentations during the Science Challenges session. This material also includes the presentations themselves, both as PDF files and as video files in which the voice of the presenter is synchronized with the display of the presentation file, except where a presenter has declined to permit open distribution.

Poster Sessions: A "Science Highlight", in lieu of an abstract is posted for each poster at http://www.iris.edu/hq/meetings/2014/06/iris_workshop_sunriver_oregon/scihi/.