Global Seismographic Network External Review

Submitted to
Incorporated Research Institutions for Seismology
Robert Detrick, President

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Table of Acronyms

ANSS	USGS Advanced National Seismic System
ASL	Albuquerque Seismological Laboratory
CTBTO	Comprehensive Test Ban Treaty Organization
DMC	IRIS Data Management Center
DS	IRIS Data Services
FDSN	International Federation of Digital Seismograph Networks
GSN	Global Seismographic Network
GSN PM	IRIS GSN Program Manager
GSN SC	IRIS GSN Standing Committee
IDA	International Deployment of Accelerometers
IGPP	Institute of Geophysics and Planetary Physics (SIO/UCSD)
IMS	International Monitoring System
IOC	Intergovernmental Oceanographic Commission
IRIS	Incorporated Research Institutions for Seismology
IS	IRIS Instrumentation Services
ITWS	International Tsunami Warning System
IUGG	International Union of Geodesy and Geophysics
NEIC	USGS National Earthquake Information Center
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PASSCAL	Portable Array Seismic Studies of the Continental Lithosphere
SAGE	Seismological Facilities for the Advancement of Geosciences and EarthScope
SIO	Scripps Institution of Oceanography
UCSD	University of California, San Diego
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey

Executive Summary

This report summarizes the deliberations of the Review Committee convened by the Incorporated Research Institutions for Seismology (IRIS) to evaluate the performance of the Global Seismograph Network (GSN). The Committee was charged to assess the present status and operations of the GSN; identify strengths, weaknesses and possible risks to its continuing operations; and consider the potential for improvements and opportunities for growth. The Committee discussed each of these charges with respect to current and future scientific goals and initiatives in the geosciences, and the delivery of the data required for comprehensive seismic monitoring.

The GSN represents the culmination of decades of both intellectual and capital investment in very high-fidelity global earthquake monitoring. Moreover, it exemplifies the concordance of two missions: providing continuous data in support of basic research in geoscience conducted primarily at U.S. academic institutions (but also internationally), and providing data in support of the specific missions of the U.S. Geological Survey (USGS) and other agencies to monitor seismic activity worldwide. The GSN has been designed and is operated to fulfill the data requirements for both missions simultaneously.

There is a special relationship between continuous seismic monitoring and basic research. While earthquakes at tectonic plate boundaries are persistent phenomena globally, great earthquakes – those of magnitude 8 or larger – are rare. There has been an increase in the occurrence of great earthquakes over the past decade, and high-fidelity on-scale recordings from the GSN have proved essential for the study of the mainshocks and the complex aftershock sequences. In addition, the availability of very high quality continuous data has led to the development of new methods of signal analysis of the entire ground motion record (including background "noise"), which have produced more highly resolved models of Earth structure and new insights on previously unknown modes of Earth deformation. This is the very definition of "discovery science," and is reflected also in the high percentage of GSN data requests among all data downloads from the IRIS data center.

None of this would have been possible without the decades of financial support provided by the National Science Foundation (NSF) and other agencies, the partnership between IRIS and the USGS, and the intellectual contributions and oversight of the research and monitoring communities. The model of a representative, university-based consortium, as conceptualized through IRIS, in combination with the overlapping monitoring mission of the USGS, has produced a seismological facility that has delivered substantially on the goals, scope and mission objectives first elucidated more than three decades ago and updated more recently. By now, more than a few "academic generations" of researchers have been trained and pursued their careers using GSN data. In return, through the IRIS committee structure, they have participated in the governance of the GSN and have built one of the strongest communities in the geosciences. The Review Committee views the current status and the various successes of the GSN as a reminder that decisive and aggressive facility support by funding agencies over the long term, in conjunction with the convening power of a cohesive, scholarly community, are fundamental requirements for both curiosity-driven and mission-oriented science.

Reflecting different institutional histories and contributions to global seismic monitoring as well as the distinct but overlapping needs for data supporting basic research and earthquake disaster response, the GSN combines the operations of the Albuquerque Seismological Laboratory (ASL) of the USGS with those of the International Deployment of Accelerometers (IDA) at the Scripps Institution of Oceanography (SIO). Project IDA's component of the GSN is funded by NSF through IRIS, while the ASL is funded through an appropriation to the USGS. While the data streams from these two operators take different paths, in both cases, the data are archived at the IRIS Data Management Center (DMC) in Seattle. The research and monitoring communities provide oversight through the governance and advisory structure of IRIS, with representation from IRIS member institutions, the USGS and other constituencies. The dual-operator model confers operational and management advantages and challenges, which the Committee has examined in this report.

As charged, the Review Committee focused its deliberations on eight main themes:

- GSN Goals;
- Technology;
- Management, Coordination and Oversight;
- Data Quality;
- Operating and Maintenance Costs;
- Partnerships;
- Scope;
- Data Management and Services.

Each theme has been examined with respect to its bearing on the research and monitoring communitie s and the prospects for greater efficiencies and cost-effective improvements.

Each thematic discussion incorporates Findings, Discussion and Recommendations. Additionally, the Committee has made some overarching comments and recommendations. Appendix A reproduces the Charge to the Committee, Appendix B contains a summary of the recommendations, and Appendix C lists the agenda governing the Committee deliberations and meetings with relevant individuals.

This document represents the consensus opinion of the Review Committee.

Introduction:

The deployment of the Global Seismographic Network (GSN) represents one of the singular achievements of the seismological community during the past thirty years. By integrating the objectives of both basic research and earthquake monitoring, the GSN, and especially its management, have shown how broad-based cooperation on technical design, recognition of operational necessities, and shared governance across academia and mission agencies can be effective and efficient at providing essential data to a broad spectrum of end-users. Over the course of its existence, the GSN has acquired data that have proved essential to new discoveries as well as state-of-the-art earthquake monitoring. It has supplied the backbone observations supporting new initiatives in the solid-earth sciences and the U.S. government's response to disastrous earthquakes. The GSN is a member of the International Federation of Digital Seismograph Networks (FDSN) and contributes data to the International Monitoring System (IMS) of the Comprehensive Test-Ban Treaty Organization (CTBTO) and to the Pacific Tsunami Warning System of the National Oceanic and Atmospheric Administration (NOAA). Other national and international agencies rely on GSN data to fulfill their mission obligations. ***Accordingly, it is the unequivocal conclusion of the Review Committee that continued federal funding of the GSN and broad community participation are essential to the future of basic and applied seismological research and the use of this research in support of agency missions. In particular, the National Science Foundation (NSF) and the U.S. Geological Survey (USGS) should act decisively to continue community engagement and stabilize with high priority their support of the GSN at levels consistent with ongoing research, expanding mission obligations and new scientific initiatives.***

As a technological descendant of earlier globally-distributed earthquake monitoring networks, the GSN has brought digital, broadband and high-dynamic range recording of Earth motions to bear on a range of frontier problems in the geosciences along with the provision of essential information for earthquake hazard assessment, disaster response, tsunami warning and verification of international nuclear non-proliferation regimes. Just as importantly, the commitment of the operating entities to open data protocols and state-of-the-art data management and archiving have enabled access to primary data for a extensive demography of end users from academia, government, non-governmental organizations and the private sector. The success of the GSN has been recognized in no small way by the continuing financial support of operations by the NSF and the USGS, and by the periodic capital investments made by NSF, USGS, the Department of Defense, the Department of Energy and other organizations.

At the time of this review, the NSF has announced that it will conduct a competition for continued operation of seismological facilities including the GSN. ***The Review Committee strongly recommends that NSF management, in drafting the terms of the competition, prioritize the importance of robust academic oversight, the***

open availability of high-quality data, continued shared operations with the USGS, and the ability of the GSN to adapt and respond to new science- and mission-oriented initiatives.

The Review Committee recognizes that continuous, decades-long support of a "monitoring network" is considered by some to be outside the scope of the NSF. ***It is thus our obligation to point out that continuous earthquake recording is as important for fundamental research as it is for mission obligations, if not more so.*** While earthquakes are global phenomena, observations of large quakes at a particular location do not constitute a statistically large set. Even more rare are truly great earthquakes, which we now know have characteristics that do not necessarily scale up from relatively common, large events. Moreover, new advances in the analysis of continuous data – including what has been previously characterized as "noise" – have illuminated new phenomena such as episodic tremor and have spawned new techniques for the imaging of Earth structure. In fact, continuous seismic recordings are now being used to study atmospheric and oceanographic phenomena and their mechanical coupling to the solid Earth. The point is that continuous monitoring has allowed the basic research community to identify previously unknown modes of Earth deformation and seismic rupture, in addition to providing wholly new ways of imaging the crust and deep Earth, and has enabled novel investigations of the oceans and the atmosphere. ***This new science by itself confirms the wisdom of continuous support of the GSN by NSF and other agencies.***

Summary Description of the GSN:

The GSN currently comprises more than 150 globally distributed stations deployed and maintained by two operators: the International Deployment of Accelerometers (Project IDA) located at the Scripps Institution of Oceanography (SIO) of the University of California, San Diego (UCSD); and the USGS's Albuquerque Seismological Laboratory (ASL). Each operator acquires data from its sub-network (through a Data Collection Center, or DCC), performs quality assurance checks, and forwards the data to the IRIS Data Management Center (DMC) for further quality control/quality assessment (QC/QA), distribution and archiving. The individual DCCs and the DMC maintain data conduits to specific end-users, including the National Earthquake Information Center (NEIC) of the USGS, NOAA's Tsunami Warning Centers, the IMS of the CTBTO, units of the Japanese Meteorological Agency and the Australian Tsunami Warning System.

The two components of the GSN are managed respectively by the Incorporated Research Institutions for Seismology (IRIS) and the USGS under a long-standing agreement to mutually coordinate operations. The GSN Standing Committee (GSN SC), populated with representatives from members of the IRIS consortium and USGS units, is used by both organizations as a joint external advisory committee. IRIS employs a GSN Program Manager (GSN PM) who ultimately is responsible for ensuring that the operations of the GSN meet the goals and objectives of the IRIS constituency. Similarly, the USGS, operating through the ASL, manages its component of the GSN to meet its mission obligations. The implications of this dual structure are discussed repeatedly throughout this report.

Process:

Beyond these general comments, this report delivers a review of the GSN as it is currently configured, focusing on operations and management of the facility, its service to basic research and its future as a foundational facility for geoscience in general and seismology in particular. Specifically, the five-year Cooperative Agreement between NSF and IRIS for operation of the Seismological Facilities for the Advancement of Geosciences and EarthScope (SAGE) specifies "a full external review of the [Global Seismographic Network], including its goals and scope, its management and operations, its technology and data quality, and its costs."[1] The charge to the review committee includes an examination of "… all associated subawards, and explor[ation of] alternative configurations, management approaches, and the possible scientific impacts."[2] Accordingly, IRIS convened a Review Committee with members appointed by the IRIS President, Robert Detrick:

Chen Ji………………………………………………………………………………….UC Santa Barbara
Colleen Dalton…………………………………………………………………….. Brown University
Florian Haslinger……………………………………… Swiss Seismological Service, ETH Zurich
Louise Kellogg……………………………………………………………………………………. UC Davis
Laura Kong………………………….. International Tsunami Information Center, Honolulu
Keith Koper…………………………………….. UU Seismograph Stations, University of Utah
Thorne Lay………………………………………………………………………………….UC Santa Cruz
Art Lerner-Lam (Chair)…… Lamont-Doherty Earth Observatory, Columbia University
Gerardo Suarez……Instituto de Geofisica, Universidad Nacional Autónoma de México

The committee met over three days from 31 March 2015 through 2 April 2015 and conducted site visits at ASL on 31 March and IDA on 1 April. The committee met for executive session on 2 April 2015 in La Jolla before adjourning. Presentations were made by the IRIS President, the IRIS Director of Instrumentation Services (Bob Woodward), and the GSN Program Manager (Katrin Hafner). The site visit to Albuquerque included presentations by and discussions with USGS personnel, including Cecily Wolfe (USGS – Reston), Jill McCarthy (USGS – Golden) and David Wilson and Bob Hutt (both at: USGS – ASL). The site visit to La Jolla was enhanced by discussions with Jon Berger, Peter Davis, and Carl Ebeling (all of Project IDA), and Peter Shearer and Guy Masters, at IGPP/SIO/UCSD. Meredith Nettles, Chair of the GSN Standing Committee, provided additional input.

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[1] "Charge to the Review Committee for the Global Seismographic Network," Page 1, also Appendix A.
[2] Ibid., page 1.

Background documents for the review were prepared and distributed by the IRIS staff and included the committee charge, an exhaustive briefing book, copies of site review presentations, several National Research Council and NSF Workshop reports, and a prior GSN Review completed in 2003 by the Pollack Committee.

Specific Findings and Recommendations:

GSN Goals:

The original concept for the GSN set forth the following goals: "*…a global network of uniformly spaced stations (~2000 km spacing), capable of recording the full range of seismic signals, with data collection in real time.*" *Are these goals appropriate, given the availability of new sensors and new sources of seismological and other geophysical data? Are these goals appropriate given the communities' research and monitoring needs over the next decade? How well does the GSN support/enable discovery science through long-term, high-quality data acquisition on a global scale?*[3]

Findings:

The original design goals have largely been met, although there are important exceptions. Developments in seismographic instrumentation generally have kept pace with the needs of the research and monitoring communities. However, in recent years, novel analyses of GSN data, new array deployment strategies, and improvements in seismographic and other geophysical instrumentation have led to new discoveries across a range of solid-earth deformation phenomena. These new discoveries, including the "Grand Challenges in Seismology" enumerated in a recent report,[4] suggest that the design goals for the GSN should be revisited in the context of both research and monitoring.

Discussion:

The original design goal for GSN station spacing has largely been met in continental areas (central Africa and Antarctica have small gaps) and in most ocean island areas, but there remain large gaps in the southern ocean basins. In some regions such as the southern Indian Ocean, current oceanic coverage is dependent upon other international networks with sparser station distributions and less reliable data delivery. While regional and international seismic networks have contributed to the density of broadband station distributions in several regions (notably Japan, Chile, Central America and Europe), few of those stations have the bandwidth and dynamic range of the IRIS primary sensors. The original intent to have a reliable, very broadband, high dynamic range, well-calibrated GSN cannot be reasonably met by a network comprising contributions from regional networks with heterogeneous

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[3] Italicized text at the beginning of each section consists of extracts from the Charge.
[4] Lay, T., ed. 2009. *Seismological Grand Challenges in Understanding Earth's Dynamic Systems*. Report to the National Science Foundation, IRIS Consortium, of a workshop held September 18-19, 2008, Denver, CO. 76pp.

instrument characteristics or other international networks with questionable reliability.[5]

Another original design goal – continuous recording of very broadband ground motions – has been met at all GSN stations. Continuous recording has proved essential for very long period normal mode analyses following great earthquakes; for discovery of unexpected very slow processes such as glacial surging and calving that go undetected by standard earthquake monitoring algorithms; and unexpected applications to seismic noise studies including the discovery of Earth's hum produced by interactions between ocean waves and the seafloor. Novel seismological methods such as cross-correlation of continuous time series to extract interstation Green's functions (that is, representations of the propagation of seismic waves between stations suitable for inversion for Earth structure) require continuous broadband signals. None of these discoveries would have been possible without the availability of continuous recording.

Telemetry of the GSN to enable real-time data processing is an updated design goal and has been met at nearly all stations, but can be dependent on minor network outages and bandwidth limits. This design goal has benefited the rapid earthquake analysis mission of the USGS's National Earthquake Information Center, including rapid moment-tensor determinations using Centroid Moment Tensor (CMT) and W-phase procedures, radiated energy estimation, and finite-faulting solutions that identify the actual fault for large earthquakes. In addition, this quantitative information is essential input for tsunami warning operations central to NOAA and the Intergovernmental Oceanographic Commission. These monitoring missions also benefit from the many federally-funded university research studies that design and test sophisticated data analysis methods that exploit the full bandwidth of the GSN instrumentation.

Although not strictly an original instrumentation or operational goal, the GSN has developed partnerships with international players with complementary observational capacities, such as the French GEOSCOPE network, or with local institutions willing to assist with operations and maintenance. A problem with this approach is that such dependence depends on the willingness of the partners to adhere to open data sharing standards, or with the partners' ability to sustain funding for their complementary operations. Any change in these relationships could impact the critical mission-oriented applications of GSN data. Thus such relationships should be reviewed critically and frequently. As a corollary, the efficiencies gained by the use of such complementary capacities suggest that there is a return on the investments made in sustaining these core international relationships.

[5] For example, the number of stations in the French GEOSCOPE network is declining and the maintenance of remaining sites is being reduced due to a weakening of financial support. The longevity of this otherwise excellent network is not ensured.

The Grand Challenges for Seismology report and other workshop and NRC reports clearly identify long-term operation of the GSN network, including oceanic coverage, as essential to sustain research and discoveries in areas of earthquake processes and global Earth structure. The reports also identify the essential role of the GSN in supporting new discoveries enabled by new modes of seismological data analysis, including the characterization of ocean-generated noise as an indicator of ocean dynamics, the collapse of glaciers, ice streams and ice shelves, and the identification and assessment of landslides in remote areas. In many instances, the GSN has provided a reference network allowing high-density regional deployments of portable instruments, regional networks, and other operational systems such as continuous GPS deployments to integrate their specific, regional observations into global model development. Given this history of GSN-enabled discovery, there is every reason to be confident that the interaction between community research and monitoring needs and GSN operations will produce additional discovery over the next decade or more.

The special relationship between continuous monitoring and fundamental research is illustrated in part by the new insights gained from studies of great earthquakes. The past decade has experienced an increasing number of great earthquakes (generally of magnitude 8 or larger) for which GSN data have proved of primary importance in analysis of the mainshock signals and have contributed to the characterization of the total earthquake sequence along with data from extant regional networks. Were it not for the existence of globally-distributed broad-band data of high dynamic range provided by the GSN, regional or national networks in most nations would be incapable of remaining operational and on-scale for these immense events. The mission objectives for monitoring agencies, such as the USGS, require the rapid assessment of earthquake size and mechanism and, for these extreme events, the GSN is the only solution. In addition, very broad-band, high-dynamic range and low noise qualities of GSN data have enabled unprecedented analysis of these complex events, leading to new insights on seismogenesis, fault rupture, fault segment interactions and tsunamigenesis.

In the Committee's view, the illumination of Earth structure and earthquake processes made possible by the GSN opens new avenues of research over the next decade. While the current design goals for basic network configuration, continuous broad-band and high-dynamic range recording, and real-time telemetry should not be relaxed, there is no question that the GSN alone cannot meet the research and monitoring needs predicted for the next decade of seismological and broader geophysical investigation of Earth structure and deformation. Recent research has shown the value of supplementing data from the GSN with observations from high-density regional networks and portable seismometer deployments, GPS data obtained from campaigns or permanent networks, hydrophone and ocean bottom seismometer arrays, pressure gauges, and infrasound deployments. At the same time, the long-term nature of GSN data collection is essential for integrating regional geophysical studies into a global context, even if those studies involve different geophysical observables.

The data provided by the GSN have been and continue to be essential to discoveries in the geological sciences. The range of science is impressive and spans investigations into the fundamental structure and dynamics of the Earth's deep structure, the physics of great earthquakes and tsunami, and includes entirely unexpected avenues of exploration such as the seismic signal of landslides and ice-stream collapse. This success is reflected in the high percentage of GSN data requests among all downloads from the IRIS data center. A large number of research papers citing GSN data were compiled into a bibliography in the GSN briefing book, but this is only a tiny fraction of papers that utilize GSN data in various earthquake source, Earth structure and environmental process investigations.[6] The ready availability of the data has also prompted a remarkable level of utilization by international colleagues, leading to a range of international collaborations that otherwise would not have occurred.

In particular, the GSN has played a critically important role in understanding the great earthquakes of the last decade, including the M>9 events in Japan and Sumatra and their consequences. Giant earthquakes are both rare and unevenly distributed in space and time. Prior to the maturation of the GSN, nearly all of the giant earthquakes of the last century produced only a handful of on-scale seismic recordings on the analog (World-Wide Standardized Seismograph Network) and early digital networks (for example, the Seismic Research Observatory network), limiting seismologists' ability to understand the nucleation, rupture characteristics and dynamics for these events. Since the deployment of the GSN, and especially in the last decade, thousands of on-scale, broad-band records have become available, providing our first real look into what is turning out to be a fundamental, dynamical component of active tectonic processes, including new classes of co- and inter-seismic phenomena that would have escaped discovery if not for the technical capabilities of the GSN. These studies have affirmed the necessity of continuous, broadband, high-dynamic range recording and telemetry. The study of giant earthquakes in such detail is still at an early stage, but hundreds of research papers using GSN data have been published in the past few years and the exponential growth of requests for GSN data indicates that this rate of discovery is not abating. It is important to recognize that this is an achievement of the entire system from the field operations to the data collection centers to the data management and distribution system; all parts of this complex system have been working synergistically to support and enable access to the data that can be used by U.S. and international researchers for discovery science.

GSN has also been critical to understanding smaller events such as the 2010 Haiti earthquake, which despite its moderate magnitude caused immense human suffering and economic disruption. No regional network was in place before the

[6] There seems to be a serious undercounting of publications utilizing GSN data. See recommendations.

event; therefore regional GSN stations were extremely important for rapid characterization of the mainshock and aftershock sequence.

It is important to note the ongoing role of the GSN in technology development for seismology in particular and broader Earth observation more generally. Through periodic renewal of hardware, development and implementation of new acquisition and communication technologies, and development of new theoretical and computational approaches to data analysis by the scientific community at large, the GSN continually contributes to transformative scientific observation and discovery. The testing and development facilities at ASL and IDA provide platforms for ongoing development of next generation very broadband sensor technology. GSN instrumentation needs have cultivated partnerships with industry, motivating instrument development efforts for very broad band sensors and ocean-bottom recording that may enable fulfillment of specific GSN design goals and further scientific discovery.

Recommendations:

1. To date, the established design goals have served both the research and monitoring communities well, and their stability over time has provided a stable target for technical innovation. However, design goals should be continuously evaluated in response to the evolution of research and monitoring needs. ***IRIS should establish a procedure that monitors community needs and technical innovation and reevaluates GSN design goals in response. Changes to design goals should occur on a timetable that allows strategic study, planning, deployment and assessment, that is, it is important that the GSN have a stable configuration for a significant (decadal, for example) period of time but not long enough to delay important design changes in response to scientific and monitoring needs.***
2. Deployment of GSN-quality instrumentation in ocean basins and on continental shelves is necessary for meeting GSN design goals and for addressing key scientific questions, but it is expensive and technically challenging. ***IRIS should convene a community effort to design and propose (to the NSF and other agencies) a pilot or demonstration project that would address these challenges and promote technological solutions while providing important scientific observations and/or addressing a particular monitoring objective. A site near a potential tsunamigenic rupture could be explored, for example.***
3. The GSN infrastructure, including data loggers, telemetry and the management and institutional relationships that provide geographically distributed and protected station sites, can be leveraged for other Earth-observing instrumentation. ***IRIS should work with the NSF and USGS to promote the use of GSN infrastructure, where appropriate, by other Earth observation communities.***

4. International collaborations play an important role not only in basic research, but also in supplementing monitoring efforts and exploring efficiencies in maintenance and operations. However, relying on international networks to help fill the necessary global coverage is risky, because the longevity of those networks and their adherence to GSN-level quality standards cannot be guaranteed. ***Discussion of design goals should solicit input from international interests.***
5. The IRIS publications database does not capture the totality of scholarly output resulting from the analysis of GSN data. This limits community and agency awareness of the significance of the GSN. We recognize that tracking use of a freely available, open dataset such as that provided by the GSN is extraordinarily difficult. ***Nevertheless, IRIS should strive to keep the GSN publication database as complete and current as possible.***

Technology:

The GSN technical specifications, established in 1985 and updated in 2002, established new standards for seismological instrumentation both nationally and internationally. *Has GSN instrumentation kept pace with new technology? Are there investments in new technology that could enhance the scientific return, performance or efficiency of the GSN? What should be the process by which technology R&D is supported and new technology is brought into the GSN?*

Findings:

GSN instrumentation is a mix of commercial off-the-shelf and purpose-built cutting-edge technology. At the same time, it is essential that the technical performance of the GSN remain stable for a reasonable period so that comparisons between different data epochs can be made. This suggests that, while the assessment of available technology should be a standard obligation of the operators and IRIS management, the incorporation of new technology into critical operations should be subjected to sober and paced reviews. At all times, seismological communities must assess the balance between research and monitoring needs, and operational efficiencies and continuity.

Near-term considerations include the decline in performance of the primary surface sensor (Streckeisen STS-1) and the primary borehole sensor (Geotech Instruments Model KS54000) and the testing, selection and rollout of their replacements; where justified by operational requirements. As of the date of the Committee meetings at IDA and ASL, new primary sensors have not yet been fully tested and approved for deployment.

Important questions include:

- How will technical specifications evolve in light of new technology?
- How will new specifications be translated into new technology?

- Will technical specifications drive or respond to new technology?
- Who will perform the necessary research and development (R&D)?
- How will new technology be assessed, capitalized and implemented?

Discussion:

The agreement by the research and monitoring communities on technical specifications for the GSN has to a large extent driven research and development in sensor and recording technology by both industry and academia. (The GSN has taken advantage of telemetry and telecommunications systems that have been developed for other, generally commercial, purposes.) With funding from NSF and other agencies, both GSN operators have made capital investments incorporating new technology, resulting in documented operational efficiencies and greater reliability. In addition, the move toward standardization of various components has simplified operations and maintenance. However, the market for GSN-level instrumentation is limited and is not by itself a reliable driver of industry R&D. Moreover, there are only a handful of academic programs that afford advanced degree students significant opportunities to conduct fundamental research in seismological instrumentation and Earth metrology more generally.

Today's state-of-the art data loggers (such as the Quanterra 330 HR) and the successful development of the replacement electronics in the primary surface sensor (STS-1) are directly related to and derived from GSN specifications. The development and testing of the STS-1 replacement and the primary borehole sensors are also motivated by GSN specifications. What is less clear is whether the R&D activities that led to these innovations represent an appropriate model for the continuous R&D and rollout needed to support new science and monitoring requirements.

Interestingly, the GSN occupies terrain between cutting-edge technology and critical operational infrastructure. This is uneasy territory, in that there is constant pressure to not get too far out ahead of reliability and operational efficiencies even though the GSN needs a testbed for new technology. These competing objectives need reconciliation. The history of R&D for the GSN is a unique blend of contributions from academia, specialized technology companies and larger industrial entities. This has been a fortuitous combination, but not necessarily a sustainable or reproducible one. It is well recognized that from the perspective of the larger industrial players, the GSN is a niche market, although GSN instrumentation might be considered a "halo product" that provides corporate distinction. The smaller players, that is those that are dependent on the R&D prowess of a very small number of individual scientists and engineers, and which have historically contributed so much to the GSN, either have been acquired by larger companies or have been overly dependent on the career trajectories and interests of their principals. This state of the R&D enterprise is not the result of any particular design strategy on the part of NSF or the GSN; rather it represents the ability of the active research and monitoring communities to rapidly assess and take advantage of technological opportunities when they arise and to influence, in a collaborative fashion, private sector R&D. That this opportunism has resulted in productive partnerships with leading companies and the individuals running them (many of them foreign to the U.S.) should be celebrated, and it has resulted in measureable benefits to both the research and monitoring enterprises. On the other hand, it is not a recipe that is easily replicated or sustained.

Contributing to this situation is the relative undersupply of university graduates with interests in seismological metrology. There are historical reasons behind this, including, somewhat counter-intuitively, the success of IRIS and the GSN and the accomplishments of the specialized technology firms. However, the future pace of GSN-motivated R&D could be limited if the necessary workforce is not educated and supported robustly.

This situation is illustrated by the incorporation of state-of-the-art telecommunication technologies into the operations of the GSN. These technologies are driven more by commercial requirements and it is simply a matter of matching capabilities and assessing costs and benefits whether they are adopted by the GSN. To date, this has been a standard mode of operations by both IDA and ASL.

It is important to restate that this mode of operations has enhanced station up-time and recording fidelity, has resulted in significant cost savings for operations and maintenance, and has improved data return in some of the harshest environments. It has also paved the way for other national and international agencies, including USGS/NEIC, NOAA/Tsunami Warning Centers, CTBTO/IMS, UNESCO/IOC, to fulfill their mission objectives at minimal marginal cost. It is incumbent, therefore, on those invested in the success of the GSN, to consider ways in which these results can be sustained.

The management of the GSN (reviewed below) recognizes these unique circumstances, some of which are in fact assets. This places the GSN in the distinctive position of being able to authoritatively convene efforts to develop technical specifications tuned to the needs of the research and monitoring communities while bearing in mind the latest research agendas and forefront initiatives aimed at next generation discovery and operations.

In addressing the question *whether there are investments in new technology that could enhance the scientific return, performance or efficiency of the GSN,* the Committee has noted that such capital investments are almost always a function of the funding available. In some ways the introduction of new technology has already enhanced performance and efficiency: capital investment as well as maintenance costs per station have dropped due to the reduced costs and increased capabilities of the new data acquisition system. However, without additional funds, current support levels are barely sufficient to maintain the network in its current status. Fronting significant development costs out of the current operating budget is not feasible, even if in the long term these developments might lead to an increase in efficiency and reduction in operations and maintenance (O&M) costs.

Independently of the IRIS/GSN budget, however, universities pursue research and development of new observational and instrumentation technologies using portfolios of private foundation and federal agency support. These efforts are motivated by new scientific needs driving new modes of Earth observation, some of which could pertain to an expanded set of GSN objectives and design goals. Although these efforts rely on the individual scientists and their labs, they present leveraging opportunities for improvements to the GSN if properly identified and assessed. For example, the development of the waveglider platform at IDA/IGPP is motivated by the desire to advance the capability for economical seismological (and other) observations in the ocean (on the ocean floor), but holds significant potential for other domains. Similarly, the development of an optical very broadband seismometer by IDA/IGPP scientists (with NSF/MRI seed money) looks very promising and may lead to new instrumentation options.

In the context of the GSN, early investments in new technology make sense in the core competence area of the GSN community (seismology); this is particularly critical for the sensors and data acquisition systems. In other areas (communication, general information technology, or other scientific domains like geodesy or infrasound) GSN should rely on developments in those specific communities, including the private sector, and be ready to adapt these developments where and when relevant. The introduction of infrasound sensors at GSN stations has already shown how the spectrum of measurements can be expanded at relatively little cost, but with significant scientific impact, showing how the data logging and telemetry infrastructure underlying the GSN can in principle support other modes of global observation.

As already noted above, instrumentation R&D as well as introduction of new technology at the GSN stations may be a direct result either of operational necessity (e.g. seismological sensor developments), or the exploitation of opportunities as they arise (e.g. introduction of new communications or power supply systems). This combination is a necessary but insufficient way of optimizing resources and capitalizing on particular skills. The lack of robust university programs in GSN-relevant instrumentation R&D, a private sector workforce dependent on a few individuals with a relatively shallow bench, and the uncertain market forces driving innovation are all risk factors.

Recommendations:

1. ***IRIS, through its Instrumentation Services division, should conduct regular technology reviews across the components of the GSN and other IRIS instrumentation and infrastructure.*** Such a review, say every few years, should include a survey of instrument research activities in universities along with commercial R&D.

2. Promising technological R&D should be presented to the relevant IRIS committees for discussion. ***Instrumentation Services should develop metrics that measure the costs and benefits associated with the deployment of particular technologies, and, for those technologies deemed ready for deployment, an implementation plan and budget.*** New technologies should be clearly linked to existing or evolving GSN program goals.
3. Instrumentation and other technical R&D in other fields, including the development of new modes of marine operations and technologies that would improve/enable deployment and O&M in oceans and other harsh environments, should be included in the regular review. ***IRIS should work with its consortium members and NSF to identify such developments, which may, in fact, be funded separately from the usual NSF programs.***
4. ***The GSN Program Manager and the IRIS Director of Instrumentation Services, together with the appropriate IRIS Standing Committees, should encourage university and commercial innovators to self-identify, perhaps through an agency or foundation partnership offering seed-money support.*** The IRIS website (and other publications) should have a page devoted to technical innovation.
5. ***The GSN and IS managers should charge their technical staff to develop professional ties with industry and university innovators, perhaps by adding side events at professional conferences and workshops and travel support for technical meetings.***
6. The testing and commissioning of new primary sensors should be accelerated. ***IRIS/IS and GSN and the USGS/Reston/Golden should develop a plan to better coordinate instrumentation testing and commissioning between IDA and ASL.***
7. ***Particular attention should be given to technical developments that might underlie a cost-effective pilot program for ocean deployments of GSN quality stations.***
8. ***NSF planning within the Geosciences Directorate at both program and major facility levels should develop a cross-disciplinary program to fund Earth observation R&D at universities, the private sector, and university-commercial partnerships***. Concerns about the future capabilities of a technical workforce could be met in part by ensuring that such programs support graduate student and post-doctoral programs.

Management, Coordination and Oversight:

The GSN includes two sub-networks operated by IRIS/IDA and USGS/ASL respectively, plus a small number of independent university-operated stations. Capital investment, installation and operational costs are supported by the NSF and the USGS. Management coordination for IRIS is provided by the IRIS GSN Program Manager. Policy oversight is provided by the GSN Standing Committee. Both IRIS and the USGS accept the GSN Standing Committee as a joint advisory committee and agree to follow the advice of the committee in good faith and to the extent possible within the limits of practical considerations and available funding. *Is the current management structure appropriate and efficient? Can it be improved, and if so, how? What significant advantages or disadvantages would there be to a substantially different management structure or mode of operation? Are subawards appropriately structured and adequately reviewed? How effective is the facility oversight by the scientific user community, especially in facilitating intermediate and long-term planning?*

Findings:

The utility of having two operators representing academia and government separately is a distinct operational advantage. This arrangement affords exceptional flexibility and opportunities in dealing with the diversity of agreements between the GSN and site hosts, which may be universities, private landholders or foreign governments. In addition to IRIS management, both the USGS/ASL and Project IDA are to be commended for being good stewards of these relationships, some of which are decades old and should be maintained.

However, the dual operator model presents challenges in addition to opportunities. These include avoiding duplication of tasks, coordinating different operational styles and blending separate mission objectives. The recent reorganization of IRIS senior management lines and the refilling of the GSN program manager position are significant managerial moves that should net efficiencies and transparency downstream, but these potential improvements are only now beginning to be realized. It will be important for the senior management of both IRIS and the USGS to periodically review coordination between IDA and ASL, and for the GSN SC to weigh the outcome of that review against the achievement of GSN goals.

It is difficult to compare the real costs of operations between ASL and IDA, because each serves different but equally important missions. The coordination of data quality assessment and data distribution through the DMC is necessary for efficiencies and serving the needs of the IRIS constituency, but the Committee is concerned whether some activities of the ASL and IDA project – including the operation of independent Data Collection Centers – are duplicative.

Although there is improvement, the activities of IDA under the sub-award suggest a perception of independence within the IRIS program. On the one hand, it is important and has proven beneficial historically that IDA, as a program within a leading academic institution, be able to take advantage of interested, institutional colleagues in ways that might lead to innovations that benefit the broader GSN program. This must be balanced against the top-level need for GSN to explore efficiencies in a budget-constrained environment by ensuring that the sub-awardee work plans stay focused and streamlined. This will continue to be a challenge for the GSN Program Manager, but if the GSN PM and the Director of Instrumentation Services take advantage of the curiosity-driven environment within which IDA sits (as well as the R&D efforts in other academic and commercial labs), this could accrue benefits to the broader GSN. (This notion parallels the above discussion under "Technology".)

The Committee finds no inherent problems arising out of the current management structure. Indeed, over its existence, the management of the GSN by IRIS has been exemplary. The recent restructuring and refilling of the full-time GSN PM is a demonstration of management evolution with an adaptive leadership responding to community oversight and the NSF Cooperative Agreement. The Committee could think of no clear option for different management structures that would demonstrably improve operational efficiencies, better serve the needs of the research and monitoring communities or improve performance under the Cooperative Agreement with NSF. In fact, the Committee is concerned that arbitrary changes to the current management structure – such as privatization – would potentially weaken community engagement (either in reality or perception), leading to a damaging drift away from the carefully formulated goals and objectives that to date have driven the success of the GSN.

Discussion:

The GSN is operated jointly by IRIS, through a subaward to Project IDA at UCSD, and the USGS, through a separate line item in the Department of Interior/USGS budget. The IDA component of the GSN consists of approximately 40 stations, and the USGS operates an additional 100 stations. The GSN is a multi-use network and is essential for basic research in Earth science as well as real-time earthquake and nuclear-test monitoring and tsunami warning. The dual-operator model of network operation helps to ensure that the needs of the research and monitoring communities are simultaneously met. IDA provides a strong link to the academic research community, and the USGS has the federal responsibility to provide monitoring and notification of seismic activity. The concurrent activities of two network operators with overlapping but different missions also allows for sharing of expertise, operational practices and software. Examples include the prototype optical borehole sensor developed by a scientist at SIO and the Data Quality Assessment (DQA) software developed by the USGS/ASL staff.

Over the course of the GSN deployments and, in fact, going back decades to the deployment of the antecedent networks, the individual relationships required to secure good station sites have been crucial to network operations. An academic operator such as IDA (together with the convening authority of the IRIS consortium) can establish relationships with station partners that might not be possible under government-to-government agreements. The reverse is also true. This flexibility has been a hallmark of the cooperative coordination between IRIS and the USGS. For example, the siting of six GSN stations in Russia in the late 1990s and station NIL-II in Pakistan were facilitated by having a university-based operator, rather than the U.S. government, initiating the discussions. Similarly, ongoing umbrella agreements between the U.S. and other nations have been important in securing sites as well as real time data access.

Community oversight and coordinated concurrent activities have turned out to be the most beneficial aspects of the current management arrangement. Having two operators permits different strengths to be shared even though the research and monitoring missions differ in detail. IDA scientists and their colleagues have used normal mode amplitudes to verify instrument calibrations, for example, while the ASL has recently developed novel data quality assessment software (DQA) that now is shared with IDA. (We note here that several members of the IRIS consortium, working with the DMC, routinely analyze GSN data in near real time and produce scientifically valuable data products with wide and international application. The Centroid Moment Tensor project is but one example.) The different perspectives on data quality that are brought to bear on the GSN data stream by the monitoring and research communities have undoubtedly contributed to the continuing fidelity of GSN data and the trust placed in the two operators. Moreover, the community oversight functions designed into the IRIS management structure have been critical to the progress on data quality, and are superb examples of the interaction between the community and the network operators.

The coordination is also evidenced by standardization of station components and adoption of common dataflow quality control procedures. Most recently, IDA has begun to use the DQA developed by the USGS, and the USGS is moving toward installing a station computer similar to the Stealth system utilized by IDA. Yet there are additional areas where further standardization should be incorporated. Importantly, the way that data issues and station status are presented to the operators, GSN PM, and user community is highly non-uniform between the USGS and IDA. Even with two operators and separate missions, the GSN should strive for integrated, uniform dissemination of station metadata.

The Review Committee recognizes that the dual-operator model results in some duplication of effort, but eliminating all duplication has not been shown to greatly reduce O&M costs. The Committee notes, for example, that the GSN Program Manager is working with IDA and ASL to develop coordinated site visits, whereby standardized instrumentation allows either operator to perform maintenance on the other operator’s station, reducing travel costs. The Committee also notes that having two operators – with two separate funding streams – provides a degree of resilience against budget restrictions as well as offering different paths for supplemental funding.

Having dual Data Collection Centers (DCCs), one at the USGS data hub in Golden, CO, and one at the IDA data hub in San Diego, CA, has its benefits[7] but could in theory increase operating costs. The Review Committee discussed whether there are efficiencies to be gained from streamlining the data collection efforts, that is, by examining in detail the data flows and quality assurance procedures practiced by

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[7] These are covered by the discussion in the “Data Management and Services” section.

individual DCCs for best practices that could be extended to all DCCs. This analysis should consider not only the IDA and USGS DCCs but also the Array Network Facility, which is a component of the EarthScope USArray project and is based at UCSD. The main goal here is to promote uniform trust in the delivered data, along with a uniform presentation of station metadata, and to introduce more across-the-board software development and routine procedures. A concomitant reduction in operating costs would be a benefit, but should not be the main driver in the Committee's opinion.

The IRIS GSN Program Manager is responsible for managing the operation of the IRIS component of the GSN, coordinating between the two network operations groups, and supporting and interacting with the GSN Standing Committee, among other tasks. As of January 2015 the GSN has a full-time (rather than part-time) PM for the first time since 2010. The Review Committee recognizes that a full-time PM dedicated entirely to the GSN is essential for the continued success of the network.

The GSN Standing Committee, comprised of members from the research and monitoring communities who serve three-year terms, is the appropriate management tool to provide substantial oversight. The GSN SC is engaged at every level of GSN operations, and provides an essential mechanism for community feedback and oversight. The progress on data quality over the past five years is a notable example of the success of this mechanism. The data-quality assessments and remote calibrations that are now a routine part of GSN operation are a direct result of input and guidance from the GSN SC.

The Committee spent a great deal of time discussing the management structure and exploring different straw-man management models. Measured against the importance of community engagement and oversight, service in support of both the research and monitoring missions, and frugal management of scarce resources, the current management structure has few weaknesses and many strengths. It is no accident that this is the result of continuing adaptation by responsive IRIS senior management over the decades of GSN operations, and change for the sake of change could do little to improve performance. Furthermore, the broad participation of the academic seismological community in IRIS management, including the participation of an enormous number of individual seismologists in the IRIS oversight committee structure, has built up over decades one of the strongest communities in the geosciences in terms of the ability to plan new scientific initiatives and facilities. While there may have been issues in the past, the current performance of both operators and IRIS management indicates the wisdom of this management approach.

The Committee discussed subaward management and structure. With the strengthening of administrative support lines in the IRIS central office, there are improved controls. Subaward management is, to our knowledge, in compliance with NSF requirements, and follows IRIS administrative procedures for internal review and approval. This is consistent with best practice principles to our understanding.

The IRIS Coordinating Committee (CoCom) provides another layer of management oversight in addition to the GSN PM and the GSN SC. The full-time GSN PM with access to subaward details provides direct oversight.

Recommendations:

1. The existing GSN management structure is performing well. ***NSF and the USGS should continue to support the dual operator model.***
2. ***A full-time Program Manager dedicated entirely to the GSN should be a permanent part of any management structure, and should have a "dotted-line" report from IRIS central administrative staff to assist in monitoring subaward performance.***
3. ***The GSN PM should work to ensure coordination of operations and maintenance between the two operators, and develop and implement plans to ensure standardized reporting of station metadata.***
4. ***The GSN PM and GSN SC should study the methods and procedures of individual DCCs and report to the IRIS BoD on the benefits and costs of promoting common QA/QC procedures and software development.***

Data Quality:

The quality of data provided by the GSN is critical to achieving the scientific goals motivating the operation of the GSN. *Are the scientific and monitoring needs of stakeholders being met? Are quality assurance systems adequate? Are there new or different strategies the GSN should adopt to ensure high quality data?*

Findings:

The network is now operating at about 90% data availability, a significant improvement mainly due to the deployment of new data loggers. Data gaps at individual stations have also been reduced. A small number of stations have been decommissioned, owing either to logistic difficulties or changes in the relationship with the local site owner. This minor level of decommissioning has not impacted the GSN mission to any significant degree.

In addition to the station hardware, data quality depends on the condition of the vault (or borehole) and other local site conditions. Some of the GSN vaults are showing signs of physical deterioration and are in need of renovation or relocation.

Quality assurance systems are a mix of procedures at the two GSN Data Collection Centers. The collection and verification of station metadata has been improved. Both rely partially on feedback from end users.

Discussion:

The open dissemination of high quality data with minimal latency has been a goal of the GSN from its conceptualization. Early in its development, more attention was placed on rapid deployments and increased station coverage than in the systematic assessment of the quality and fidelity of the data. As the network, GSN management and community oversight matured, data quality problems were detected and a strong effort was made to implement quality assessment and quality control protocols on the data stream and to develop routine data examinations – such as the quality assessment accompanying the Global CMT – that would provide near immediate feedback on data quality. These efforts have achieved a level of data quality that is now almost taken for granted by both research and monitoring communities. These end users have a degree of confidence in the quality of the data stream that is reinforced by the proactive oversight supplied by the GSN SC, Instrumentation Services, and the DMC SC.

The results obtained to date by the GSN are commendable. The DMC developed the *Modular Utility for Statistical Knowledge Gathering (Mustang)* tool and, in parallel, the USGS developed the *Data Quality Assessment Analysis (DQA)* tool. Today, IDA, the USGS and the DMC are testing the quality assessment software routinely to verify data quality. These tools identify various problems such as high noise levels, channel polarity errors and metadata inaccuracies. They have been helpful in identifying the continued degradation of the STS-1 primary sensors. It is important to underline that these tools complement one another and measure different metrics and variables in the waveforms and the metadata. However, procedural duplication and overlap should be identified and assessed, and several members of the Committee expressed a desire to see a more uniform, integrated presentation of data quality across the network.

The research and monitoring communities have played an important and active role in supporting the GSN in the quality assessment efforts. IRIS formed a *Quality Assessment Working Group (QAWG)* and Lamont-Doherty´s *Waveform Quality Center (WQC)* routinely informs IRIS of problems encountered when performing the inversions for centroid moment tensors*.* These two entities interact with both research and monitoring functions and provide essential feedback to the GSN on data quality issues. In addition to these tools, GSN operators have implemented maintenance procedures to ensure a better quality standard of the data, including a ticket system for tracking problems. An important contribution is the fact that a new instrument calibration policy was instituted based on the ability of the new digitizers to accept remote requests for calibration.

These efforts have resulted in improving the quality of the data distributed by the DMC and also advise users of potential problems in archived legacy data.

While these efforts have diverse strengths, the Committee discussed the importance of a common data and metadata quality tool integrating the best features of existing software. It would also be useful to systematize feedback mechanisms that would simplify data quality assessments from researchers not involved in the line processing of the data stream.

Quality assessment and control by itself is a first step to improving quality of the resulting data. It is essential, however, to upgrade and replace aging and unreliable equipment. A recapitalization effort with the new primary sensors now being tested will be necessary to ensure the long-term quality of the GSN data. To this end, the continued improvement of the data quality assessment tools that identify problems with data should help prioritize investments in upgrading and refurbishing the instruments and the supporting installations and civil works of the seismic stations.

Recommendations:

1. ***GSN should develop plans to integrate QC, QA and metadata collection and verification to the extent possible, in order to provide end users with a common tool that presents a uniform view of GSN data quality and uniform access to metadata.*** This should develop into a standard operating protocol for the GSN data stream. Where feasible, input from other networks should be solicited, and the needs of the PASSCAL community might also be addressed.
2. ***In addition to the feedback provided by the CMT, NEIC and other routine data product producers, GSN should explore methods to solicit and aggregate feedback from the broader user community.***
3. While the GSN SC is presumably kept well-informed of GSN performance, it would benefit broader awareness of the GSN if a more public view of real time network performance and data quality could be made available, although this is of lower priority. In particular, ***the daily distribution of useful data quality and metadata metrics (State of Health, for example) would benefit some specific users as well as improve awareness of the excellent performance of the GSN. These reports should be aggregated by the GSN PM (and perhaps be included as a function of IRIS IS), rather than distributed by the two operators.***
4. Data stream quality control protocols are useless if the station hardware is not functioning. ***NSF, IRIS and the USGS should work together to ensure that funds are available for recapitalizing station hardware when and where appropriate and in a timely manner. Continuing assessments of station vault and borehole conditions are also necessary.***

Costs:

A major challenge for the long-term sustainability of the GSN will be to contain operational and maintenance costs. *Are costs appropriate and well substantiated? Are current staffing levels appropriate and well substantiated? Are there alternative management or operational models that could significantly reduce costs without negative impacts? Are there investments in new technologies that could help minimize future operational and maintenance costs?*

The current model for recapitalization is to obtain support outside regular core funding. Is this model adequate to meet the future needs of the network? Are there other models that should be considered?

Findings:

Operational and maintenance (O&M) costs are driven both by management efficiencies and the performance and reliability of instrumentation components. Costs are also related to the speed with which new, perhaps more efficient components can be brought on-line and deployed. The Committee finds that the O&M costs of both the ASL and IDA components are as low as they can be without compromising overall system performance. More importantly, it is clear that the ability to test and deploy new components that might be more efficient is constrained by overall budget levels and the uncertain future of instrument R&D. Arbitrarily capping O&M costs is a poor strategy.

Discussion:

The NSF has made a substantial investment in the GSN and related functions of the DMC. For the five-year period ending 30 June 2014 (IRIS FY), IRIS Core Expenditures have been $23.0M, which includes IDA expenditures of $15.1M, and USGS/ASL Core expenditures have been $25.3M summing to $48.3M (or $9.7M/yr). Station O&M costs comprise approximately 75% of the budget, with DCC and DQ activities being the next largest sum. Operational costs per station are comparable for both components of the GSN. (This amounts to approximately $65K/yr/station, but includes several rounds of equipment refurbishment and replacement and thus is not reflective of the annualized operational costs over the life of the network.)

The Committee examined to the extent time and resources allowed the expenditures of each of the operators and the IRIS core related to GSN. There is no indication of unexplained charges, nor is there any indication that costs are excessive. Indeed, it was stressed repeatedly by all concerned, including the entirety of the committee, that IRIS/GSN and USGS/ASL were acting in accordance with good management principles under a constrained budget. Given normal salary increases, which in this case are not excessive, and the normal inflationary growth of other portions of the budget, it is remarkable that the GSN is performing as well as it is. The Committee stresses that capped or declining budgets are the most significant problem facing the GSN.

An immediate consequence of budget constraints is the increasing burden being placed on personnel associated with the GSN. Both IDA and ASL have reduced the number of field technicians, for example, leading to an imperative for the GSN PM to more strongly coordinate O&M field trips between the two operators. (One additional issue is the different regulations regarding foreign travel promulgated by the USGS and the NSF cooperative agreement with IRIS. These differences also suggest that coordinated field management is important.)

As noted frequently throughout this report, another consequence of constrained budgets is the extra load placed on IRIS and the USGS to find funding for the deployment of new, possibly cost-saving technology. Both operators have cleverly leveraged partnerships to reduce service and telemetry costs, and they have, of course, been able to address some of the recapitalization issues by requesting and receiving funds from other agencies. But the *ad hoc* nature of this approach does not allow strategic, multi-year budgeting and planning.

The savings realized by the deployment of the new data logger are manifest in the reduced downtime and related maintenance, but are not yet easily quantifiable. The need for rapid testing, commissioning and deployment of a new primary sensor is undeniable, but “break-in” costs associated with any new instrument cannot be estimated. It concerns the Committee that neither IRIS nor the USGS have room in their GSN budgets for a reasonable contingency fund.

The Committee concludes that it is unlikely that a new GSN management or operational model could significantly reduce costs without compromising performance. Indeed, it is difficult to operate at the current funding level without compromising performance. There are few degrees of freedom or incentives within IRIS to increase the top line of the GSN budget, given the demands of the other IRIS programs, but an overall examination of the budget distribution among the major IRIS programs could lead to a rebalancing of program budgets that could benefit the GSN without inducing problems in other units. This analysis is outside the scope of the Committee’s charge, but is an important future requirement of IRIS’s senior management.

Major recapitalization of network hardware is an unbudgeted expense under the current management and operating model. While the Committee understands that it is not common federal practice to allow depreciation or the accumulation of funds for eventual equipment replacement, it is still not a best practice principle for the operation of a major ongoing facility. Both NSF and the USGS should plan to secure funds in their program budgets that could eventually be allocated in response to solicited or unsolicited proposals from the community. It is fair to say that much of these costs can be anticipated several years in advance, and NSF and the USGS could task the communities with keeping the agencies up to date on future recapitalization expenses.

That said, the Committee commends both IRIS and the USGS for seeking opportunities outside their normal funding streams to secure funds for new stations and the recapitalization of older sites. While this takes management time and, it could be argued, contributes to overhead costs, there appear to be no other options available at the present time. However, the Committee notes that there does not seem to be any planning for the funding required for the renovation or relocation of older vaults and boreholes when site conditions impair data quality.

Recommendations:

1. The committee sees no alternative management models that would significantly reduce costs without negative impact. However, ***IRIS senior management and the Board of Directors should be encouraged to critically review the budget distribution among the major programs and prioritize near-term issues across the programs.***
2. ***The GSN Program Manager should work with both operators to review the schedule of O&M station visits and develop mutually agreeable travel schedules and itineraries.***
3. ***The GSN PM and IRIS Director of IS should develop a plan to assess station site conditions that impact data quality and data return, and develop cost estimates for renovation or relocation.***
4. ***NSF and the USGS should be encouraged to include GSN equipment recapitalization costs in their multi-year program budget plans.*** The procedures used by major facilities in the Ocean Sciences or other divisions and directorates might be adopted as funds allow.
5. ***In the absence of NSF and USGS program action to fund recapitalization, IRIS and USGS senior management should continue to explore funding opportunities from other agencies and foundations.***

Partnerships:

In addition to the IRIS-USGS partnership, partnerships with other FDSN networks are essential to provide global coverage in areas not covered by the GSN. GSN data are also utilized by other U.S. government agencies, including NOAA and DOE. *Are there ways to improve collaborations between the GSN and other networks that would enhance utility or improve efficiency?*

Findings:

The Committee finds that the ability of IRIS and the USGS to develop partnerships through bilateral peer-to-peer academic relationships, government-to-government formal agreements or national networks and international federations has been a largely unheralded contributor to the GSN. Partnerships have helped the GSN secure expanded station coverage, create operational efficiencies, and promote open data sharing.

The International Federation of Digital Seismograph Networks (FDSN)[8] is an important convener and enables technical cooperation among regional, national and global network operators. The list of participating organizations and their scientific and technical representatives is impressive, and includes several IRIS employees

[8] http://www.fdsn.org

(and a member of the Review Committee). The Committee finds the FDSN to be an important vehicle for the GSN and the connection should be maintained.

Some partnerships have long histories and are considered stable. Others may be less so. The Committee did not conduct a risk analysis of the existing GSN partnerships. Knowledge about the quality and sustainability of existing partnerships resides mainly with a few individuals and not, to any great degree, formally with IRIS management.

Cooperative cost-sharing arrangements with host countries may have some potential for sustaining GSN, but for those stations that are located in developing nations or remote sites, there is limited potential to secure more than current levels of partner participation in the network.

The Committee finds that leveraging the GSN to promote individual capacity building exercises with university consortium members and partners has led to new modes of funding, interest from agencies in addition to the NSF (Department of State and US Agency for International Development, for example), serving the dual purpose of promoting member proposals to these agencies while at the same time helping the GSN meets its goals.

Despite long-standing discussions, outreach to other network types (such as strong motion networks or other non-geophysical observing networks), does not appear to have resulted in significant relationships.

Discussion:

The Committee raises a conundrum associated with "partnership risk:" partnerships, whether they be operational or research collaborations, rightly play an important role in the operation of the GSN and in the conduct of basic research and earthquake monitoring using GSN data. On the other hand, the GSN fulfills, in part, U.S. strategic goals (for example, for earthquake monitoring through the USGS and nuclear test ban treaty verification through the CTBTO), which cannot depend entirely on external (foreign) partners. Partnerships, especially with foreign governments (less so with foreign universities), are subject, as past experience suggests, to bi-lateral and multi-lateral relationships that may be outside of the control of IRIS and USGS management. This is not easy to resolve, and continuing communication among the controlling parties is essential to the continuity of GSN operations. This is especially important for the continued operation of sites in Eurasia and will likely be important if the GSN ever extends coverage into the oceans.

From the beginning, external partners have played critical roles complementing and augmenting the mission of the GSN. These partners have come from all aspects of the data chain – station hosts that collect and share data, public and private sector data telemetry providers, scientist users of the raw data, and finally, decisionmakers and public consumers of the information products derived from GSN data. These partners represent research universities, and government and non-government agencies across the US and internationally.

For seismic monitoring at the international level, in addition to the IRIS-USGS partnership, partnerships with other FDSN networks continue to be essential to provide complementary global station coverage in areas not serviced by the GSN. The importance of the FDSN lies in its convening authority and promotion of technical discussions among the various network operators. The FDSN ably provides this avenue of collaboration notwithstanding its voluntary nature and lack of a budget.

IRIS and a succession of GSN managers have long recognized that national earthquake monitoring networks, when sustained and producing high-quality data, offer opportunities to expand GSN station coverage and create O&M efficiencies. Through US NSF support, and often in concert with individual members of the consortium, IRIS continues to build the national capabilities of developing countries to monitor, evaluate, and manage earthquake risk by themselves. This capacity building is a win-win because it builds the human resource skills of countries hosting GSN stations, and in doing so, helps to reduce long-term station maintenance costs, as well as ensuring real-time, high-quality data flow.[9]

Beyond the scientific and technical collaborations required to collect and share data, the GSN continues to be a US ambassador fostering and building multi-lateral relationships at the political level between and among countries. Innovative leveraging of communications technologies, such as the GCI under the CTBTO for the IMS, is a further example of how GSN has embraced partnerships to contribute to a global seismographic asset for many end users. By focusing on natural hazards and the shared international responsibility to address risk through science-based assessments, IRIS and its GSN have established themselves as a global reservoir of best practices that transcend political boundaries.

Additional sustained collaborations between the GSN and partner global or regional networks will bring in more data and will densify station coverage, increasing the potential for new discovery. Where there is duplicative station coverage with other networks, this affords IRIS the possibility of sharing maintenance costs, or possibly even closing stations (as long as mission capabilities are not compromised). Similarly, sharing telemetry costs with other networks is a way for IRIS to reduce operational costs.

Existing collaborations, such as with international organizations like the CTBTO, UNESCO IOC for tsunami warning, and other coordinating groups concerned with seismicity (under IUGG) need to be continued, improved and deepened wherever

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[9] See http://www.iris.edu/hq/publications/meeting _materials, especially the list under "International Development Seismology."

possible. At the regional level, IRIS GSN could also explore relationships with organizations that serve the needs of countries of a specific region, such as the CDEMA (Caribbean), SPC/SOPAC (Pacific), or ASEAN (Southeast Asia))[10].

Successful and fruitful partnerships will require IRIS to understand the needs of each partner, and work with them to provide services that will be valued and be meaningful to them over the long-term. Each partner will probably require specific approaches. Sharing and building capacities can be leveraged by coordinating with university partners in the U.S. and abroad, as evidenced by the recent successes in Chile and in Sub-Saharan Africa with AfricaArray.

GSN data are also utilized by other U.S. government agencies, including NOAA and DOE. NOAA, which has the statutory responsibility to issue tsunami warnings, depends on the GSN for real-time data for monitoring global seismicity and assessing tsunamigenic potential, but it is unrealistic to expect major additional investment. This is in large part because the USGS is tasked with the statutory responsibilities of collecting real-time data to support global earthquake monitoring, which it then shares with NOAA (Tsunami Warning, Education, and Research Act [2015, proposed]; 2006 Tsunami Warning and Education Act); for the same reasons, NOAA would not see a requirement to enter into an MOU with IRIS for real-time seismic data to support its tsunami warning mission.

Recommendations:

1. ***IRIS and the USGS should work together to conduct a partnership inventory and risk assessment.*** Such an assessment should include technical, economic and political factors that would impact GSN operations and affect open and real-time access to data. The risk assessment should be made available to the GSN SC (and other standing committees and oversight boards as appropriate).
2. ***US representatives on FDSN committees should ask for an assessment of potentially duplicative activities across the member networks of the Federation***, in the context of looking for opportunities to reduce recapitalization, deployment and ongoing O&M costs.
3. Following past practice, ***IRIS should leverage opportunities presented by its membership to expand GSN station coverage or promote national partnerships that might reduce O&M costs,*** following the examples of Chile and AfricaArray. The former IRIS Development Seismology Committee and Director of Planning played significant roles in exploring connections with the Department of State and USAID. ***IRIS should reexamine whether there are ad hoc or standing governance structures that could assess leveraging opportunities.***

[10] CDEMA: Caribbean Disaster Emergency Management Agency; SPC/SOPAC: Applied Geoscience and Technology Division of the Secretariat of the Pacific Community; ASEAN: Association of Southeast Asian Nations

4. ***The GSN PM should examine existing partnerships, as part of the risk assessment, for collaborative strategies that could be applied across the board to other relationships.***
5. ***Senior management of IRIS should encourage IRIS's foreign affiliates to further develop their respective national seismographic capacities in ways that could supplement GSN coverage, operations and maintenance.*** While this could be accomplished also through the FDSN, the IRIS Foreign Affiliates Program could provide the venue for a more focused discussion.
6. Although prospects are uncertain, continuing discussions with NOAA and the CTBTO concerning support of O&M costs are worthwhile. ***This is a general recommendation for IRIS senior management.*** Similarly, opportunistic discussions with the managers of other regional, national or global Earth observing networks should be a general responsibility of both IRIS and NSF management.

Scope:

The GSN now consists of 153 stations. Combined with stations of cooperating FDSN networks (especially GEOSCOPE, Pacific 21, GEOFON and MedNet) and cooperation with the CTBTO IMS network, the coverage on land has reached that envisioned in the original GSN siting plan. Coverage in oceanic regions remains sparse. *What are the most significant challenges to the GSN over the next decade? Is the process for re-evaluation of the GSN siting plan adequate? What efforts, if any, should be undertaken to encourage the installation of sustainable seismic observatories on the seafloor? Are activities to encourage the installation of other types of sensors at GSN site adequate and appropriate?*

Findings:

The Committee agrees unanimously that the most significant challenge facing the GSN is the continuation of high-quality operations under stagnant budgets[11]. In such a budget environment, which NSF maintains will exist into the foreseeable future, many of the findings and recommendations enumerated in other sections of this report reflect an unyielding community desire to maintain the GSN's scope while looking for additional funding outside the main collaborative agreement that could broaden that scope. Any "descoping" of the GSN that derived only from budget constraints (that is, not supported technically or by community-driven changes in goals) would not be in the best interests of discovery science or U.S. earthquake monitoring obligations. It would not be hyperbolic to apply the label "tragic" to such an outcome.

[11] We note with concern the levels of funding for the NSF GEO Directorate in the FY16-17 NSF authorization act and the FY16 House and Senate appropriation bills, as of the date of this writing.

With that message in mind, the Committee finds that continuing community engagement in regularly reviewing goals and scope is one of the most important functions of the IRIS consortium. This must be sustained.

Coverage on the seafloor remains an important expansion of scope, if not an imperative. There have been many recent advances in ocean bottom seismographs, and there are developments in underwater robotics that may help reduce marine O&M costs. A pilot or demonstration project is required, possibly with contributions from the Ocean Sciences division in NSF/GEO.

New modes of array analysis and advanced array deployment strategies offer tantalizing opportunities to expand the scope of the GSN. These have not been fully explored. These include newly commissioned national and regional networks, long-duration PASSCAL and other portable array deployments, and USArray-style "marching deployments" spanning both continents and selected ocean basins.

Activities to encourage other types of sensors could be strengthened. The GSN infrastructure, apart from serving geophysical observatories, may also permit other Earth observation technologies – such as ecosystem, atmospheric or even astronomical observations. NSF could consider instituting an agency-wide review of the physical facilities and cyber-infrastructure underlying global observing networks to see if there are any commonalities and leveraging opportunities.

Discussion:

GSN data have become so entrained in day-to-day research and monitoring activities that several important constituencies would challenge any reduction in scope immediately. There is considerable and well-founded concern that flat or declining budgets – at the top-lines of NSF/GEO, EAR and IRIS and at the USGS – will negatively impact GSN operations in the near term. Reductions in existing scope and reduced opportunities for expanding the scope are distinct possibilities. Of course, one way to address this is with the constant search for new efficiencies within the current GSN structure, as this Committee has been asked to determine. Another approach requires an examination of the budget balancing among the IRIS programs as well as among EAR programs. However, the Committee suggests that the time frames over which any of these conversations occur must be synchronized and coordinated so that IRIS, NSF and the USGS can utilize proactive community inputs. Delays in testing, commissioning and deploying new primary sensors will affect the scope and have been discussed previously. Additionally, constraints on available funding will restrict new initiatives to design an ocean bottom pilot or demonstration project. These are very near-term challenges. A longer-term challenge to the GSN (and IRIS more generally) is that the real and perceived future budget lines, not to mention the year-to-year variability and disruptions caused by federal stalemates and continuing resolutions, vitiate long-term planning, a necessity for the continuity of operations, realistic discussions of scope and the continued engagement of the community. Sustaining a “GSN identity” is an important way of engaging the community in a reevaluation of scope.

Despite the dark budget clouds, or, perhaps because of them, it is encouraging that the academic community continues to propose new initiatives, elucidate new “Grand Challenges,” and contemplate new facilities (including expanded GSN scope) to address future research needs and enhance discovery science. For example, supplementing the GSN with novel array deployments could help to illuminate undersampled regions of Earth’s interior. Improved coordination and data sharing with FDSN members may reduce O&M costs. New initiatives such as the nascent Subduction Zone Observatories may provide a focus for the expansion of GSN scope into the oceans.

To the Committee’s knowledge, IRIS is at the table for most of these discussions, but we have not yet seen a comprehensive discussion of the seismographic infrastructure that would underlie these advances. We presume, based on past experience, that there will be GSN-related infrastructure – and thus an expanded scope – that could service these initiatives collectively.

Ocean sites, in particular, need serious discussion. IRIS has shown the capacity to develop network technology for harsh site conditions (Greenland and Antarctica are examples) and, with the expertise accumulated in the Ocean Bottom Seismology Instrument Pool, could work with the GSN SC to explore the design of a demonstration project. At this time, the Committee sees no budget scenario or instrument design that would allow for a permanent ocean basin addition to the GSN scope. However, building on the technical advances achieved by the Ocean Observatories Initiative might be one way of developing a suitable pilot deployment.

The Committee was impressed with the rational approach taken by the GSN SC in monitoring station performance and prioritizing the GSN siting plan. The standing committee – with information provided by the GSN PM – examines factors such as the capacity of the local partner, the condition of the vault, urban encroachment, and the costs of continued operations relative to GSN goals and scope. This has resulted in the closing or relocation of several sites in ways that have not compromised goals.

Recommendations:

1. Frequent review of the GSN scope, including siting considerations, should encourage broader community engagement on a more frequent basis. ***The GSN SC should be charged with developing a community engagement plan.***
2. ***NSF should coordinate, and IRIS could help convene, an agency-wide review of Earth-observing networks.*** Such a review would explore the potential for common infrastructure (such as telecommunications and siting) that might lead to reduced O&M costs.

3. ***The GSN SC should be charged with reviewing the outcomes of recent workshops on grand challenges and new instrumentation and address the impact of workshop recommendations on GSN scope and planning.***

Data Management and Services:

IRIS Data Services (DS) has the responsibility to provide access to all GSN data. In addition, as part of its commitment to the FDSN, IRIS is a permanent FDSN archive for continuous data from the FDSN Backbone Network and provides coordinated access to data from many FDSN stations. *Are there ways the interactions among IRIS DS, the two DCCs and the GSN could improve data quality and access/utility? Could the data collection system be streamlined to reduce costs without serious negative impacts? Are there different or additional capabilities for data access or data quality that the GSN and DS should provide? How effective are the linkages between the IRIS DMC and other global, national and regional data centers?*

Findings:

The Committee finds that GSN management, the IRIS DMC and the two GSN operators work together and individually to develop advanced tools for assessing data quality and station performance. In some cases, however, this information is not aggregated in ways that would be useful either to end-users or to GSN management.

The presence of two DCCs presents opportunities and challenges. The Committee finds that the opportunities outweigh any perceptions of overt redundancies if the work of the two DCCS is properly coordinated. Combining the two DCCs into one unit probably would not afford significant cost savings or improved operational efficiencies.

The Committee finds that existing linkages with other global, national and regional data centers are effective in making additional data available to the GSN constituencies, but there may be additional opportunities in developing bilateral linkages with other scientific, engineering and monitoring communities.

Discussion:

Making high quality observations has always been a key GSN goal. Over the past 10 years, significant efforts have been made by GSN management to develop and implement a more holistic approach to data quality. The new software tools referenced in the Data Quality discussion above were developed to calculate data quality metrics from direct analysis of the GSN data streams. Additional sensors deployed at each station supply measurements of important parameters affecting instrument performance, such as internal temperature, humidity, and barometric pressure. This wealth of information, combined with feedback from end-users, if uniformly aggregated, is a resource that could be used by the operators to improve network performance and efficiency.

The two separate Data Collection Centers (DCC) operated by ASL/NEIC at USGS and IDA at UCSD are in principle coordinated by the GSN PM and the GSN SC, and are integral to IRIS DS. The Committee sees the benefit in integrating DCC activities. For example, the USGS operation ensures that the needs of other U.S. and international agencies are met, especially for tsunami warning systems and the obligations to nuclear-test-ban treaty monitoring organizations. Similarly, the demands of academic research impose important controls on data quality and access, which are being addressed by the IDA operation. The Committee noted that though communication between the DCCs has improved recently, in many aspects the DCCs still act separately. This might be expected because of the different missions and constituencies, but there are implications for data quality and access. For example, both groups have recently improved station calibrations, but the station-specific calibration parameters are found separately on either of the websites operated by IDA and the USGS. Uniform records of station calibrations and other station metadata for the entire GSN network should be available to users at the IRIS DMC, and perhaps mirrored at NEIC/ASL.

The Committee did not have the time to explore in fine detail current DCC operations in order to make specific recommendations for streamlining operations. However, the Committee recognizes that the DCCs have a strong history of opportunistically leveraging external resources (such as the sharing of low-cost telemetry at Alert, Canada) and recommends continued efforts in this area when prudent. The Committee feels that attempting to combine the two DCCs into a single DCC could have serious negative impacts and may in fact turn out to be more expensive because of the significant in-kind support and leveraging authority provided by both the USGS and UCSD. Thus the issue for the Committee is not whether the two DCCs should be combined, but how they should be coordinated to maximize opportunities for better performance and efficiencies. Maintenance of two DCCs makes the GSN more resilient and robust, key attributes for a scientific facility that must be operated continuously over decades.

Since the two DCCs have different but overlapping missions, their approaches to data quality control and data access derive from different and overlapping perspectives. This is a strength of the current system in that it provides additional capabilities for the QA/QC assessments and delivery mechanisms available to end-users. It is the sense of the Committee that this organizational structure enhances the quality of the data and provides both the research and monitoring communities with different opportunities to provide feedback to the operators. As has already been noted, however, it places additional burdens on the GSN PM and the GSN SC to periodically review the standards and practices applied by both DCCs and to effectively coordinate between them. This is particularly relevant in the case of station calibrations and other metadata.

As we noted in the section on Partnerships, the GSN is a member of the FDSN and interacts with test-ban treaty monitoring networks. The effectiveness of these links ought to be measured by the amount of additional data (of high quality) that is made available to the GSN constituencies. The IRIS DMC archives most of the data from these networks. IRIS and the FDSN remain – along with several other international partners – central to maintaining an ethic of open access to the data across several networks. On the other hand, overreliance on foreign networks with uncertain futures or networks with tightly-defined missions driven by political considerations can be a risk factor when measured against the overarching goals of the GSN. That said, the Committee discussed the degree to which IRIS and the USGS maintain liaisons with these other networks and data centers and found no factors – other than staff time – that would substantially improve the effectiveness of these linkages.

One option, which the Committee did not explore in detail, might be the degree to which the GSN works with PASSCAL, EarthScope, the USGS ANSS/regional networks, and other regional network initiatives to explore ways in which novel array deployments could enhance global coverage and the illumination of significant seismological targets. The DMC archives most of the data from these networks but until recently, there has been little discussion of how these data could contribute to or even augment GSN strategic goals. The Committee notes, however, that recent community workshops on novel array deployments and analytical methods may lead down this path.

The Committee notes that the strong ground motion community generally is not yet aware that the GSN has recorded and archived high sampling rate strong ground motions for up to 30 years in some cases. This dataset is valuable for many engineering studies and might attract additional support for the maintenance of the strong motion sensors.

Recommendations:

1. ***The Committee recommends maintaining separate IDA and USGS DCCs.***
2. ***The Committee encourages the IDA and USGS DCCs and the EarthScope Array Network Facility to maintain and strengthen recently implemented synergistic activities*** such as technical interchange meetings, exchange of data quality software, and general communication about best practices. ***The Committee encourages IRIS to consider these activities in its annual evaluation of DCC performance.***
3. IRIS, working through the IS and DS committees and the GSN PM, should continue to emphasize the holistic approach to data quality as well as the aggregation of uniform data quality metrics and station metadata. In particular, ***the GSN PM should work with the two DCCs to better coordinate data quality assessment procedures. The GSN PM should also work with the DMC to develop a single portal for access to station calibrations, other***

metadata and quantitative station quality information. The portal should offer end-users a structured way to submit feedback on data quality.

4. The DCCs should continue to look for opportunities for prudent leveraging of external resources as a way to reduce costs and improve data collection. ***Such opportunities should be coordinated with the GSN SC and GSN PM.***
5. ***The Committee suggests that the IRIS DMC consider establishing a link with Center for Engineering Strong Motion Data (CESMD),*** a cooperative center established by the USGS and the California Geological Survey (CGS), in order to provide raw and processed strong-motion data for earthquake engineering applications. Such a link could expand the user base for GSN data.

Concluding remarks:

This report is being written as NSF and the academic Earth science community consider new solid-earth research initiatives, the geophysical instrumentation that would support those initiatives, and the recompetition to operate existing seismological facilities (SAGE), including the GSN, that have served the seismological research and monitoring communities for the past few decades. At the same time, the Committee is well aware of the heightened scrutiny of facility operations that is part and parcel of the constrained U.S. budget environment affecting federal agencies including the NSF and the USGS. While additional money can produce a response to many of the recommendations of this report, we are not so naïve to suggest that improvements in the efficiency and quality of GSN operations are achieved by more funding alone.

However, it is clear to every member of the Review Committee that the current state of the GSN is a supremely successful achievement, representing not only the wishes of the research and monitoring communities, but, also, serving as a model of institutional cooperation among IRIS, the NSF, and the USGS with input and continued guidance and oversight provided by an active and dedicated community of users. ***That a single network can provide essential data for discovery science as well as crucial support for the statutory responsibilities of the USGS is a marvel of technology, participatory governance, and institutional coordination. The Committee applauds IRIS and USGS management and the staffs of Project IDA and the ASL for their commitments to strategic goals, excellence in day-to-day operations, and their interactions with their respective and common constituencies, all while dealing with limited resources.***

The recommendations presented here are meant to be incremental and constructive. As with any complex endeavor, there is always room for improvement. However, we wish to make it clear that the basic organizational and operational fabric of the GSN, especially with the recent restoration of a full-time GSN Project Manager, is strong and responsive to community and agency interests. ***It is difficult to see how significant restructuring could improve service at lower cost. In fact, it is remarkable that so much is being done with so little.*** While there are certainly significant issues that could impact future data quality (delays in the deployment of a new primary sensor come to mind), ***the institutions now in place are well positioned to explore most avenues for operational improvements and new efficiencies, including the search for new revenues.***

The strength of the IRIS-USGS-NSF-community framework is rooted in the familiarity and trust built up over the more than three decades of GSN operations. In particular, the governance and oversight infrastructure now in place has demonstrated how the active and continuous engagement of data users results in consensual goals and responsive operations. ***Any recompetition must result in an institutional structure that prioritizes this engagement***.

In the judgment of this Committee, any reduction in costs arising from a recompetition is unlikely and will not be substantially different from the marginal cost reductions achieved by implementing a few of this report's recommendations. ***Indeed, it is the view of this Committee that prior investments in the GSN have returned dividends in discovery science and earthquake monitoring well above the integrated monetary value of the facility.*** Such scientific and operational returns should signal to IRIS, the USGS, the NSF and other agencies that additional investment is warranted. Without such investment, maintenance and operations will suffer, and innovation will be stalled.

Acknowledgments:

The Committee benefited greatly from the very substantial efforts of Bob Detrick, President of IRIS, Bob Woodward, IRIS Director of Instrumentation Services, and Katrin Hafner, GSN Program Manager. Together with their respective staffs, they prepared a substantial briefing book, helped develop the site visits and agendas for meetings, and assisted the Committee in understanding the nuances of GSN operations and the relationships among the operators and agencies. We thank Cecily Wolfe, Jill McCarthy and David Wilson of USGS headquarters, the NEIC, and the ASL, respectively, for their assistance and cogent presentations. We also thank the staffs of the IDA Project at the Scripps Institution of Oceanography and the Albuquerque Seismological Laboratory for providing time, space and assistance during the review. We thank Meredith Nettles, Chair of the GSN SC for an insightful briefing and profound discussion.

Appendix A

Charge to the Review Committee for the Global Seismographic Network

GSN Review

The Review Committee for the Global Seismographic Network (GSN) is charged with providing a full external review of the GSN, including its goals and scope, its management and operations, its technology and data quality, and its costs. The Committee is asked to provide recommendations and advice to the IRIS Board of Directors and President, and to the National Science Foundation (NSF), on ways to maintain the quality and improve the operations, efficiency and scientific return of the network. The review should take a long-term perspective and consider how to ensure the continued viability of the network and quality of operations over the next decade.

While the primary purpose of the committee is to review and report on those activities that fall under the IRIS/NSF program, it is recognized that the GSN is a collaborative project that includes the U.S. Geological Survey (USGS) and international partners. It is also recognized that GSN data are used by other U.S. government agencies such as NOAA and DOE. NSF and IRIS will work closely with the USGS to ensure that the deliberations of the committee and the implementation of its recommendations are coordinated with those activities of the GSN that involve the USGS and other U.S. government agencies. International GSN partners and the Federation of Digital Seismographic Networks (FDSN) will be informed of the review, invited to provide input and provided with a summary of the Committee's recommendations.

Major emphasis will be placed on the Global Seismographic Network itself – i.e. "operations, personnel and instrument costs" as supported through the IRIS GSN Program. However, the review also should include those activities related to quality control and data management and distribution related to the GSN that fall under IRIS Data Services.

Mandate

The Cooperative Agreement (CA) between the IRIS Consortium and the National Science Foundation requires IRIS to: *"By the end of the second year of this CA, conduct a full external review of the GSN, including all associated subawards, and exploring alternative configurations, management approaches, and the possible scientific impacts. The review will be developed and carried out in collaboration with the USGS. The Awardee will keep the NSF Program Officer informed throughout the process."*

Membership

The committee will be appointed as specified under Article V, Section 4 of the IRIS By Laws, which states: "*The President may appoint advisory committees or panels to* *assist in carrying out the business of the Corporation*".

The Review Committee for the Global Seismographic Network will consist of a Chair plus six members. Members of the committee will be appointed by the IRIS President in consultation with the IRIS Board of Directors, the Program Director for SAGE (Seismological Facilities for the Advancement of Geoscience and Earthscope) award at the National Science Foundation and the Program Coordinator for the GSN program at the USGS.

Members will be chosen to minimize real or perceived conflicts of interest with IRIS or the GSN network operators

Schedule

It is anticipated that the committee will meet and prepare its report during the first quarter of 2015. A final report will be presented to IRIS by April 15, 2015 for review by the IRIS Board at their May 2015 meeting. The review committee report, and an IRIS response, will be submitted to NSF on or before September 30, 2015.

The committee will be briefed by IRIS Program staff and governance (including representatives of the Board of Directors, GSN and DMS Standing Committees), representatives of the GSN network operators, and other interested parties. If required, site visits will be arranged to network operations centers in San Diego and Albuquerque and the Data Management Center in Seattle.

The Committee will be provided with written documentation on the history and current status of the GSN and budgetary information.

Key Questions

In fulfilling its charge to conduct "a *full external review of the GSN, including all associated subawards, and exploring alternative configurations, management approaches, and the possible scientific impacts"*, the committee is asked to address the following questions. The committee has the latitude to address other questions if they are relevant to this charge.

GSN Goals

The original concept for the GSN set forth the following goals: "*a global network of uniformly spaced stations (~2000 km spacing), capable of recording the full range of seismic signals, with data collection in real time*".

- Are these goals still appropriate in light of advances over the past 10 years in availability of new sensors and data types (e.g. availability of high-quality regional and international seismic networks, geodetic networks)?
- Are these goals appropriate given community research and monitoring needs for the next decade?

- How well does the GSN support/enable discovery science through long-term, high-quality data acquisition on a global scale?

Technology

The GSN technical specifications, established in 1985 and updated in 2002, established new standards for seismological instrumentation both nationally and internationally.

- Has GSN instrumentation kept pace with technological development?
- Are there investments in new technology that could enhance the scientific return, performance or efficiency of the GSN?
- What should be the process by which technology R&D is supported and new technology is brought into the GSN?

Management, Coordination and Oversight

The Global Seismographic Network includes two sub-networks, IDA and USGS, operated by IRIS and USGS respectively, plus a limited number of independent university-operated stations. Capital equipment, installation and operational costs are supported by the NSF and the USGS. Management coordination for IRIS is provided by the IRIS GSN Program Manager. Policy oversight is provided by the GSN Standing Committee. Both IRIS and the USGS accept the GSN Standing Committee as a joint advisory committee and agree to follow the advice of the committee in good faith and to the extent possible within the limits of practical considerations and available funding.

- Is the current management structure appropriate and efficient? Can it be improved, and if so, how?
- What significant advantages or disadvantages would there be to a substantially different management structure or mode of operation?
- Are subawards appropriately structured and adequately reviewed?
- How effective is the facility oversight by the scientific user community, especially in facilitating intermediate and long-term planning?

Data Quality

The quality of data provided by the GSN is critical to achieving the scientific goals motivating the operation of the GSN.

- Does the GSN provide data of sufficient quality to meet the scientific and monitoring needs of the community?
- Are quality assurance systems adequate?
- Are there new or different strategies the GSN should adopt to ensure high-quality data?

Costs
A major challenge for the long-term sustainability of the GSN will be to contain operational and maintenance costs.

- Are current costs appropriate and well substantiated?
- Are current staffing levels appropriate and well substantiated?
- Are there alternative management or operational models that could significantly reduce costs without negative impacts?
- Are there investments in new technologies that could help minimize future operational and maintenance costs?
- The current model for recapitalization is to obtain support outside regular core funding. Is this model adequate to meet the future needs of the network? Are there other models that should be considered?

Partnerships
In addition to the IRIS-USGS partnership, partnerships with other FDSN networks are essential to provide global coverage in areas not covered by the GSN. GSN data are also utilized by other U.S. government agencies, including NOAA and DOE.

- Are there ways in which improved collaborations between the GSN and other global or regional networks could enhance global seismological observations and/or improve the efficiency of the GSN?
- Are there other collaborations with U.S. government agencies (e.g. NOAA in tsunami early warning) or international organizations that should be developed or improved?

Scope of GSN
The GSN now consists of 153 stations. Combined with stations of cooperating FDSN networks (especially GEOSCOPE, Pacific 21, GEOFON and MedNet) and cooperation with the CTBT IMS network, the coverage on land has reached that envisioned in the original GSN siting plan. Coverage in oceanic regions remains sparse.

- What are the most important challenges that the GSN faces over the next 10 years?
- Is the process for re-evaluation of the GSN siting plan adequate?
- What efforts, if any, should be undertaken to encourage the installation of sustained seismic observatories on the seafloor?
- Are activities to encourage the installation of other types of sensors at GSN sites adequate and appropriate?

Data Management and Services

IRIS Data Services (DS) has the responsibility to provide access to all GSN data. In addition, as part of its commitment to the FDSN, IRIS is a permanent FDSN archive for continuous data from the FDSN Backbone Network and provides coordinated access to data from many FDSN stations.

- Are there ways in which interaction between IRIS DS (including the Data Collection Centers operated by the USGS and IRIS) and the GSN program could improve data quality or accessibility?
- Could the data collection system be streamlined to reduce costs without serious negative impacts?
- Are there different or additional capabilities for data access or data quality that the GSN and DS should provide?
- How effective are the linkages between the IRIS DMC and other global, national and regional data centers?

Appendix B
List of Recommendations

Goals:

1. To date, the established design goals have served both the research and monitoring communities well, and their stability over time has provided a stable target for technical innovation. However, design goals should be continuously evaluated in response to the evolution of research and monitoring needs. ***IRIS should establish a procedure that monitors community needs and technical innovation and reevaluates GSN design goals in response. Changes to design goals should occur on a timetable that allows strategic study, planning, deployment and assessment, that is, it is important that the GSN have a stable configuration for a significant (decadal, for example) period of time but not long enough to delay important design changes in response to scientific and monitoring needs.***
2. Deployment of GSN-quality instrumentation in ocean basins and on continental shelves is necessary for meeting GSN design goals and for addressing key scientific questions, but it is expensive and technically challenging. ***IRIS should convene a community effort to design and propose (to the NSF and other agencies) a pilot or demonstration project that would address these challenges and promote technological solutions while providing important scientific observations and/or addressing a particular monitoring objective. A site near a potential tsunamigenic rupture could be explored, for example.***
3. The GSN infrastructure, including data loggers, telemetry and the management and institutional relationships that provide geographically distributed and protected station sites, can be leveraged for other Earth-observing instrumentation. ***IRIS should work with the NSF and USGS to promote the use of GSN infrastructure, where appropriate, by other Earth observation communities.***
4. International collaborations play an important role not only in basic research, but also in supplementing monitoring efforts and exploring efficiencies in maintenance and operations. However, relying on international networks to help fill the necessary global coverage is risky, because the longevity of those networks and their adherence to GSN-level quality standards cannot be guaranteed. ***Discussion of design goals should solicit input from international interests.***
5. The IRIS publications database does not capture the totality of scholarly output resulting from the analysis of GSN data. This limits community and agency awareness of the significance of the GSN. We recognize that tracking use of a freely available, open dataset such as that provided by the GSN is extraordinarily difficult. ***Nevertheless, IRIS should strive to keep the GSN publication database as complete and current as possible.***

Technology:

1. ***IRIS, through its Instrumentation Services division, should conduct regular technology reviews across the components of the GSN and other IRIS instrumentation and infrastructure.*** Such a review, say every few years, should include a survey of instrument research activities in universities along with commercial R&D.
2. Promising technological R&D should be presented to the relevant IRIS committees for discussion. ***Instrumentation Services should develop metrics that measure the costs and benefits associated with the deployment of particular technologies, and, for those technologies deemed ready for deployment, an implementation plan and budget.*** New technologies should be clearly linked to existing or evolving GSN program goals.
3. Instrumentation and other technical R&D in other fields, including the development of new modes of marine operations and technologies that would improve/enable deployment and O&M in oceans and other harsh environments, should be included in the regular review. ***IRIS should work with its consortium members and NSF to identify such developments, which may, in fact, be funded separately from the usual NSF programs.***
4. ***The GSN Program Manager and the IRIS Director of Instrumentation Services, together with the appropriate IRIS Standing Committees, should encourage university and commercial innovators to self-identify, perhaps through an agency or foundation partnership offering seed-money support.*** The IRIS website (and other publications) should have a page devoted to technical innovation.
5. ***The GSN and IS managers should charge their technical staff to develop professional ties with industry and university innovators, perhaps by adding side events at professional conferences and workshops and travel support for technical meetings.***
6. The testing and commissioning of new primary sensors should be accelerated. ***IRIS/IS and GSN and the USGS/Reston/Golden should develop a plan to better coordinate instrumentation testing and commissioning between IDA and ASL.***
7. ***Particular attention should be given to technical developments that might underlie a cost-effective pilot program for ocean deployments of GSN quality stations.***
8. ***NSF planning within the Geosciences Directorate at both program and major facility levels should develop a cross-disciplinary program to fund Earth observation R&D at universities, the private sector, and university-commercial partnerships***. Concerns about the future capabilities of a technical workforce could be met in part by ensuring that such programs support graduate student and post-doctoral programs.

Management, Coordination and Oversight:

1. The existing GSN management structure is performing well. ***NSF and the USGS should continue to support the dual operator model.***
2. ***A full-time Program Manager dedicated entirely to the GSN should be a permanent part of any management structure, and should have a "dotted-line" report from IRIS central administrative staff to assist in monitoring subaward performance.***
3. ***The GSN PM should work to ensure coordination of operations and maintenance between the two operators, and develop and implement plans to ensure standardized reporting of station metadata***.
4. ***The GSN PM and GSN SC should study the methods and procedures of individual DCCs and report to the IRIS BoD on the benefits and costs of promoting common QA/QC procedures and software development.***

Data Quality:

1. ***GSN should develop plans to integrate QC, QA and metadata collection and verification to the extent possible, in order to provide end users with a common tool that presents a uniform view of GSN data quality and uniform access to metadata.*** This should develop into a standard operating protocol for the GSN data stream. Where feasible, input from other networks should be solicited, and the needs of the PASSCAL community might also be addressed.
2. ***In addition to the feedback provided by the CMT, NEIC and other routine data product producers, GSN should explore methods to solicit and aggregate feedback from the broader user community.***
3. While the GSN SC is presumably kept well-informed of GSN performance, it would benefit broader awareness of the GSN if a more public view of real time network performance and data quality could be made available, although this is of lower priority. In particular, ***the daily distribution of useful data quality and metadata metrics (State of Health, for example) would benefit some specific users as well as improve awareness of the excellent performance of the GSN. These reports should be aggregated by the GSN PM (and perhaps be included as a function of IRIS IS), rather than distributed by the two operators.***
4. Data stream quality control protocols are useless if the station hardware is not functioning. ***NSF, IRIS and the USGS should work together to ensure that funds are available for recapitalizing station hardware when and where appropriate and in a timely manner. Continuing assessments of station vault and borehole conditions are also necessary.***

Costs:

1. The committee sees no alternative management models that would **significantly reduce costs without negative impact. However, *IRIS senior***

management and the Board of Directors should be encouraged to critically review the budget distribution among the major programs and prioritize near-term issues across the programs.

2. ***The GSN Program Manager should work with both operators to review the schedule of O&M station visits and develop mutually agreeable travel schedules and itineraries.***
3. ***The GSN PM and IRIS Director of IS should develop a plan to assess station site conditions that impact data quality and data return, and develop cost estimates for renovation or relocation.***
4. ***NSF and the USGS should be encouraged to include GSN equipment recapitalization costs in their multi-year program budget plans.*** The procedures used by major facilities in the Ocean Sciences or other divisions and directorates might be adopted as funds allow.
5. ***In the absence of NSF and USGS program action to fund recapitalization, IRIS and USGS senior management should continue to explore funding opportunities from other agencies and foundations.***

Partnerships:

1. ***IRIS and the USGS should work together to conduct a partnership inventory and risk assessment.*** Such an assessment should include technical, economic and political factors that would impact GSN operations and affect open and real-time access to data. The risk assessment should be made available to the GSN SC (and other standing committees and oversight boards as appropriate).
2. ***US representatives on FDSN committees should ask for an assessment of potentially duplicative activities across the member networks of the Federation***, in the context of looking for opportunities to reduce recapitalization, deployment and ongoing O&M costs.
3. Following past practice, ***IRIS should leverage opportunities presented by its membership to expand GSN station coverage or promote national partnerships that might reduce O&M costs,*** following the examples of Chile and AfricaArray. The former IRIS Development Seismology Committee and Director of Planning played significant roles in exploring connections with the Department of State and USAID. ***IRIS should reexamine whether there are ad hoc or standing governance structures that could assess leveraging opportunities.***
4. ***The GSN PM should examine existing partnerships, as part of the risk assessment, for collaborative strategies that could be applied across the board to other relationships.***
5. ***Senior management of IRIS should encourage IRIS's foreign affiliates to further develop their respective national seismographic capacities in ways that could supplement GSN coverage, operations and maintenance.*** While this could be accomplished also through the FDSN, the IRIS Foreign Affiliates Program could provide the venue for a more focused discussion.

6. Although prospects are uncertain, continuing discussions with NOAA and the CTBTO concerning support of O&M costs are worthwhile. ***This is a general recommendation for IRIS senior management.*** Similarly, opportunistic discussions with the managers of other regional, national or global Earth observing networks should be a general responsibility of both IRIS and NSF management.

Scope:

1. Frequent review of the GSN scope, including siting considerations, should encourage broader community engagement on a more frequent basis. ***The GSN SC should be charged with developing a community engagement plan.***
2. ***NSF should coordinate, and IRIS could help convene, an agency-wide review of Earth-observing networks.*** Such a review would explore the potential for common infrastructure (such as telecommunications and siting) that might lead to reduced O&M costs.
3. ***The GSN SC should be charged with reviewing the outcomes of recent workshops on grand challenges and new instrumentation and address the impact of workshop recommendations on GSN scope and planning.***

Data Management and Services:

1. ***The Committee recommends maintaining separate IDA and USGS DCCs.***
2. ***The Committee encourages the IDA and USGS DCCs and the EarthScope Array Network Facility to maintain and strengthen recently implemented synergistic activities*** such as technical interchange meetings, exchange of data quality software, and general communication about best practices. ***The Committee encourages IRIS to consider these activities in its annual evaluation of DCC performance.***
3. IRIS, working through the IS and DS committees and the GSN PM, should continue to emphasize the holistic approach to data quality as well as the aggregation of uniform data quality metrics and station metadata. In particular, ***the GSN PM should work with the two DCCs to better coordinate data quality assessment procedures. The GSN PM should also work with the DMC to develop a single portal for access to station calibrations, other metadata and quantitative station quality information. The portal should offer end-users a structured way to submit feedback on data quality.***
4. The DCCs should continue to look for opportunities for prudent leveraging of external resources as a way to reduce costs and improve data collection. ***Such opportunities should be coordinated with the GSN SC and GSN PM.***
5. ***The Committee suggests that the IRIS DMC consider establishing a link with Center for Engineering Strong Motion Data (CESMD),*** a cooperative center established by the USGS and the California Geological Survey (CGS), in order to provide raw and processed strong-motion data for earthquake engineering applications. Such a link could expand the user base for GSN data.

Appendix C

GSN Review

Version 7, 03/27/2015

Monday, March 30:

- Committee members travel to Albuquerque, arrive in late afternoon; check-in at Hotel Andaluz, Dinner for all participants at 6:30 PM - *MÁS at Hotel Andaluz*

Tuesday, March 31 – Hotel Andaluz – Majorca Room

7:30 – 8:00 Breakfast
8:00 – 8:15 Introductions, Identification of key objectives and format of the review (Lerner-Lam)
8:15 – 8:35 IRIS Management overview – (Detrick/Woodward)
8:35 – 8:55 USGS Management overview (McCarthy)
8:55 - 9:40 GSN overview – (Hafner/Woodward)

9:40 – 9:50 **Break**

9:50 – 10:20 Current Perspective from the GSN SC (Nettles)
10:20 - 12:00 Questions and Discussion

12:00 - 13:30 **Lunch and travel to ASL**
13:30 – 14:00 Overview of ASL operations & discussion (Wilson)
14:00 – 15:45 Tour of ASL (Wilson) (also: Bob Hutt)
15:45 – 16:00 Final discussion and questions
16:00 – 17:00 Executive Session of Committee

17:00 **Travel Back to Hotel**

18:00 Working Dinner for Review Committee – *Tucanos Brazilian Grill (110 Central Ave NW)*

Wednesday, April 1

- Morning - travel to San Diego – meetings to be held in T-29 (Martin Johnson House)

12:30 - 13:30 Lunch – working lunch for committee
13:30 - 14:30 Overview of IDA operations (Davis/Berger)
14:30 - 15:30 Tour of IDA facilities
15:30 - 16:00 Discussion and Questions
16:00 - 17:00 Executive Session of Committee for end of day wrap-up
18:00 Working dinner for Review Committee – *Barbarella Restaurant (2171 Avenida De La Playa)*

Thursday, April 2

8:00 – 17:00 committee deliberations and report writing
IRIS management, IDA Management, Dave Wilson
and Meredith Nettles available for follow-up Q&A, etc. until ~11:00 a.m.

(LUNCH with Guy Masters and Peter Shearer, IGPP/UCSD)
Additional discussions with:
Robert Detrick
Bob Woodward
Katrin Hafner
Meredith Nettles

Evening Working dinner for Review committee in San Diego

Friday, April 3

Committee members travel to home destination