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The Global Seismographic Network Surpasses Its Design Goal

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This year, the Global Seismographic Network (GSN) surpassed its 128-station design goal for uniform worldwide coverage of the Earth. A total of 136 GSN stations are now sited from the South Pole to Siberia, and from the Amazon Basin to the sea floor of the northeast Pacific Ocean—in cooperation with over 100 host organizations and seismic networks in 59 countries worldwide (Figure 1).

Established in 1986 by the Incorporated Research Institutions for Seismology (IRIS) to replace the obsolete, analog Worldwide Standardized Seismograph Network (WWSSN), the GSN continues a tradition in global seismology that dates back more than a century to the network of Milne seismographs that initially spanned the globe. The GSN is a permanent network of state-of-the-art seismological and geophysical sensors connected by available telecommunications to serve as a multi-use scientific facility and societal resource for scientific research, environmental monitoring, and education for our national and international community.

All GSN data are freely and openly available via the Internet both in real-time and from archival storage at the IRIS Data Management System (www.iris.edu).

GSN instrumentation is capable of measuring and recording with high fidelity all of Earth's vibrations, from high-frequency, strong ground motions near an earthquake, to the slowest free oscillations of the Earth (Figure 2). GSN seismometers have recorded both the greatest earthquakes on scale (for example, the 1994 Mw-8.2 Bolivia earthquake at 660 km depth; *Wallace* [1995]), as well as the nano-earthquakes ($M < 0$) near the sea floor at the Hawaii-2 Observatory [*Butler*, 2003]. GSN sensors are accurately calibrated, and timing is based on GPS clocks.

The primary focus in creating the GSN has been seismology. However, the power, telemetry, site, and logistical infrastructure at GSN stations are inherently multi-use. These resources are available to other scientific sensors, and the GSN welcomes interest from other scientific disciplines in sharing this infrastructure. GPS, meteorological, and geomagnetic sensors currently enhance GSN sites as geophysical observatories.

Global Telemetry and Partnerships

Global real-time telemetry from all stations is the second GSN design goal now within reach. Dial-up telephone access, which the GSN pioneered in the early 1990s, has largely been supplanted by Internet and satellite access, which has now reached more than 80% of the network. To achieve this telemetry coverage, a wide range of solutions—geosynchronous satellites employing antennas in the 1 to 4 m range, Inmarsat, Iridium, land lines, local ISPs, submarine cable, etc.—has been implemented, in cooperation with NASA/Jet Propulsion Laboratory, the U.S. National Imaging and Mapping Agency, the U.S. National Weather Service, Japan's National Research Institute for Earth Science and Disaster Prevention, and the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO). GSN has taken the lead in establishing Internet infrastructure in Siberia, Mongolia, Gabon, the Galapagos, and Pitcairn Island. Satellite hubs in Houston and at the Pacific Tsunami Warning Center in Honolulu collect and forward data from South America, Africa, and the Pacific.

Seismology became a global science more than a century ago. The GSN is a major facility in support of this global science, and benefits from international cooperation with many partners who contribute resources in many ways. Through IRIS, the GSN is a founding member of the Federation of Broadband Digital Seismographic Networks (FDSN), which has served to help coordinate siting of global stations among member networks, and to establish an international data exchange format for seismic data (SEED).

However, at the most basic level, the GSN cooperates internationally through its individual relationships with its 136 stations. Many GSN stations are cooperatively operated as part of joint international collaboration with other FDSN member networks, or as a part of the national or regional networks within the host nation. These cooperative efforts result in the contribution of seismic equipment, telemetry, and other support in kind that has enhanced GSN stations above and beyond the funding from the United States. These international partners include network operators in Australia, Brazil, Canada, China, France, Germany, Great Britain, Italy, Japan, Kazakhstan, Kyrgyzstan, Korea, Mexico, New Zealand, Norway, Peru, Russia, Spain, and others such as the Observatories and Research Facilities for European Seismology (ORFEUS).

Network Operations

The GSN was established by the IRIS Consortium of 101 universities in the United States through funding from the National Science Foundation, and through a Memorandum of Understanding with the U.S. Geological Survey (USGS), which provides operations and maintenance support for about two-thirds of the network. The primary network operations centers are at the USGS Albuquerque Seismological Laboratory and the University of California at San Diego, both of which operated predecessor network infrastructure upon which the GSN was built [*Peterson and Hutt*, 1989; *Agnew et al.*, 1986].

Nine stations in the United States, Germany, Botswana, Singapore, and Antarctica have joined the GSN as affiliates, providing all of the necessary equipment to meet design goals and funding their own operations and maintenance. Four of these affiliates in the United States add array capabilities to the GSN—three arrays are operated by the Air Force Technical Applications Center, and a fourth is operated by Southern Methodist University as part of the International Monitoring System (IMS) of the CTBTO.

Global Monitoring

Established as a multi-use scientific facility, the GSN serves an essential function for earthquake and nuclear treaty monitoring and for tsunami warning. It is a fundamental resource in the compilation of catalogs and bulletins of earthquake locations by the USGS National Earthquake Information Center. Rapid access to GSN data has led to rapid analysis of earthquake mechanisms, bringing public awareness of earthquakes as well-documented, accurate scientific events; not just news events. GSN data are critical to the public and government agency response to earthquakes, tsunamis, and volcanoes,

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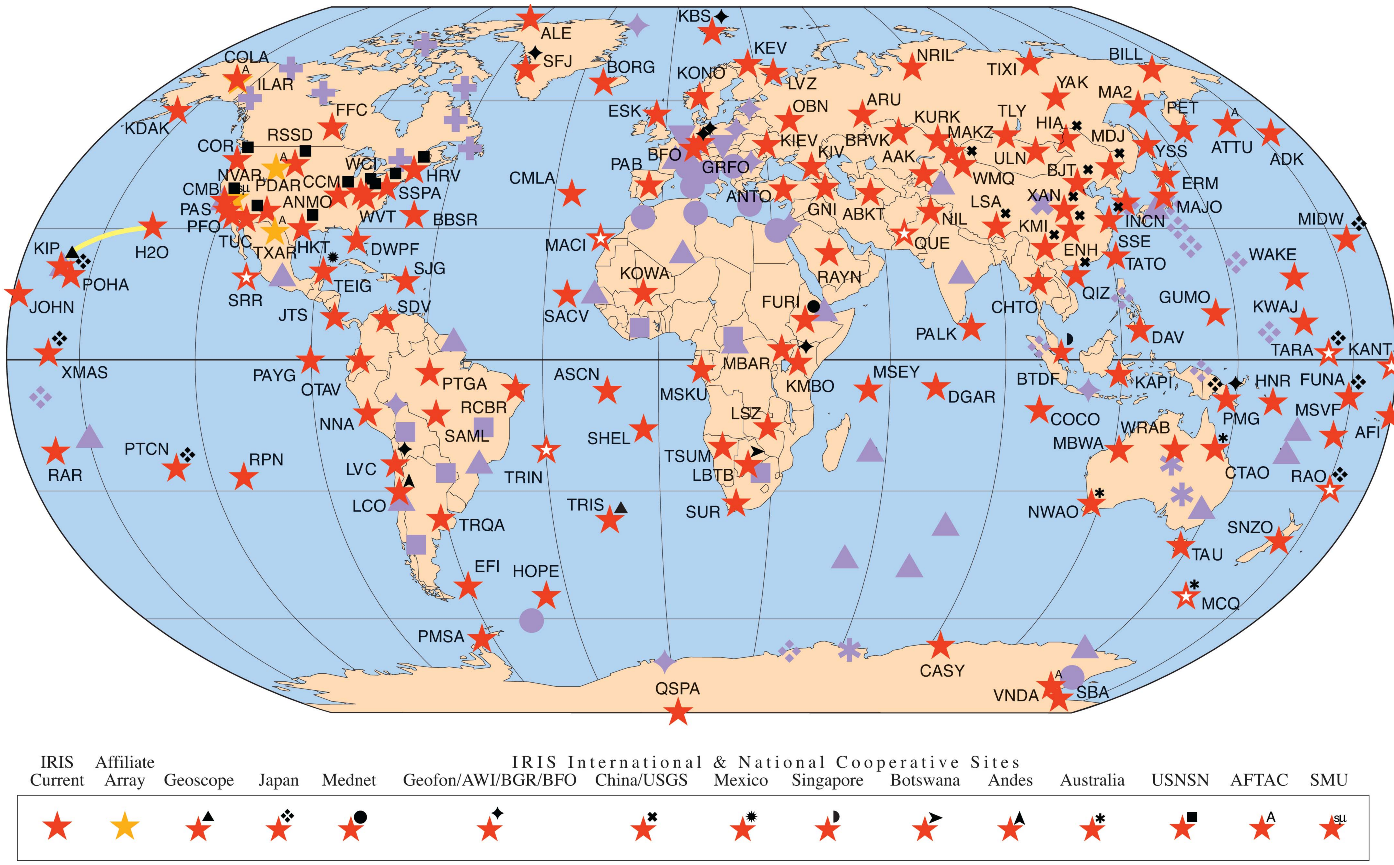

Fig. 1. Locations of the current GSN stations (red stars) and GSN affiliate arrays (orange stars) are shown, as well as sites planned for completion in the coming years (red-white stars). The site code name is indicated. The H2O sea floor site is connected to Hawaii by a re-used undersea telephone cable. GSN is a founding member of the Federation of Digital Seismic Networks (purple symbols) and coordinates with FDSN in station siting and open data exchange. Many GSN stations are cooperative with other networks, indicated by the symbol on the "shoulder" of the star.

and as a resource in mitigating earthquake hazards.

The openly available GSN data are routinely used by national and international nuclear treaty verification and monitoring programs. Over 50 stations have been designated by the CTBTO as sites for participation in the Auxiliary Network of the IMS. In cooperation with CTBTO, data from these stations are now beginning to flow to the International Data Centre in Vienna via its global communications infrastructure, which is also being shared to provide the GSN with data access to its sites for remote operations and maintenance and quality control.

H2O

The Earth is dominantly an oceanic planet. The GSN has achieved its coverage almost entirely from sites on the continents and from islands, but it has also taken the lead in establishing the Hawaii-2 Observatory (H2O) on the sea floor between Hawaii and California, using the Hawaii-2 retired submarine telephone cable donated by AT&T [*Butler et al.*, 2000]. While the H2O station is currently the only GSN site on the sea floor, the GSN is actively involved in the upcoming Ocean Observatory Initiative (ORION) to establish new sea floor sites using this observatory infrastructure of cable, buoys, and portable arrays. Truly uniform seismic coverage of the Earth requires a presence in the oceans.

Seismology

The seismic recordings obtained by the GSN, combined with data from other regional and national seismic networks, have been used in analyses of thousands of earthquakes around the globe. GSN data are the primary data used in the systematic determination of the Harvard Centroid-Moment Tensor Catalog [e.g., *Ekström et al.*, 2003] and the USGS Moment Tensor Catalog [e.g., *Sipkin*, 1994], which have enjoyed vast applications in seismotectonics. Body and surface waves recorded by GSN stations have contributed to hundreds of studies of individual rupture processes, including detailed inversions of finite-faulting parameters for major earthquakes such as the 1992 Landers (California), 1999 Turkey, 2001 India, 2002 Denali (Alaska), and 2003 Hokkaido events, among many more. Rapid access to the GSN data enabled by real-time telemetry has enabled earthquake slip characterizations to be determined within minutes to hours of large events, augmenting emergency response activities and assessment of aftershock potential.

GSN data have played a major role in studies of all parts of the Earth's interior. Broadband GSN data have been used to study heterogeneous anisotropic structure of the inner core, velocity gradients in the outer core, and the possibility of pockets of light materials ponded beneath the core-mantle boundary. GSN data have been critical for global investigations of structure in the core-mantle transition zone, revealing the presence of acute thermal and chemical heterogeneity, anisotropy, and probable partial melting.

Successive generations of mantle tomography models have been developed using GSN recordings of body waves, mantle waves, and free oscillations, unveiling the large-scale structure of Earth's interior, and prompting new models of mantle dynamics and chemical evolution. Global mapping of topography on mantle discontinuities has been achieved using GSN data, and local and global tomography has revealed the deep structure of continental roots, back-arcs, and spreading ridges. Broadband GSN data have contributed to the mapping of upper mantle and crustal layering and anisotropy, with the permanent stations providing long-term measurements that give anchor points for portable deployments. Global aspherical models of upper mantle attenuation have been produced using GSN data, as well as global models of anisotropy in the lithosphere and asthenosphere. Local and regional recordings of earthquakes have been used to model lateral variations in the crustal wave guide. Indeed, no region of the Earth has gone unexplored by GSN data, and it is sobering to pause and imagine where the discipline of seismology would be had the GSN not been established. Similarly, projecting into the future, one can imagine the great and exciting contributions yet to be made by future GSN data, which will affirm the importance of sustaining this network.

The goal of the GSN is to provide real-time access to excellent, very-broadband seismic data with uniform coverage from a fiducial global network that is efficiently operated and maintained for science. This framework now exists. *Jon Peterson* [1995], former chief of the USGS Albuquerque Seismological Laboratory, succinctly stated the challenge to the GSN: "Past experience has shown that the transition from development and deployment to operation and maintenance is a critical period in the life of a global seismograph network. It is far easier to generate enthusiasm and funding for the development of new technology than for its year-to-year maintenance. The World-Wide Standardized Seismograph Network (WWSSN), which was equivalent to the GSN in scope and impact, began its demise one year after the last station was installed in 1967."

The challenge that the GSN faces is shared by the entire seismological community. Active, vocal, and visible support by the community that uses the GSN is required. Please acknowledge the GSN whenever and wherever you publish using any GSN data, referencing this *Eos* article.

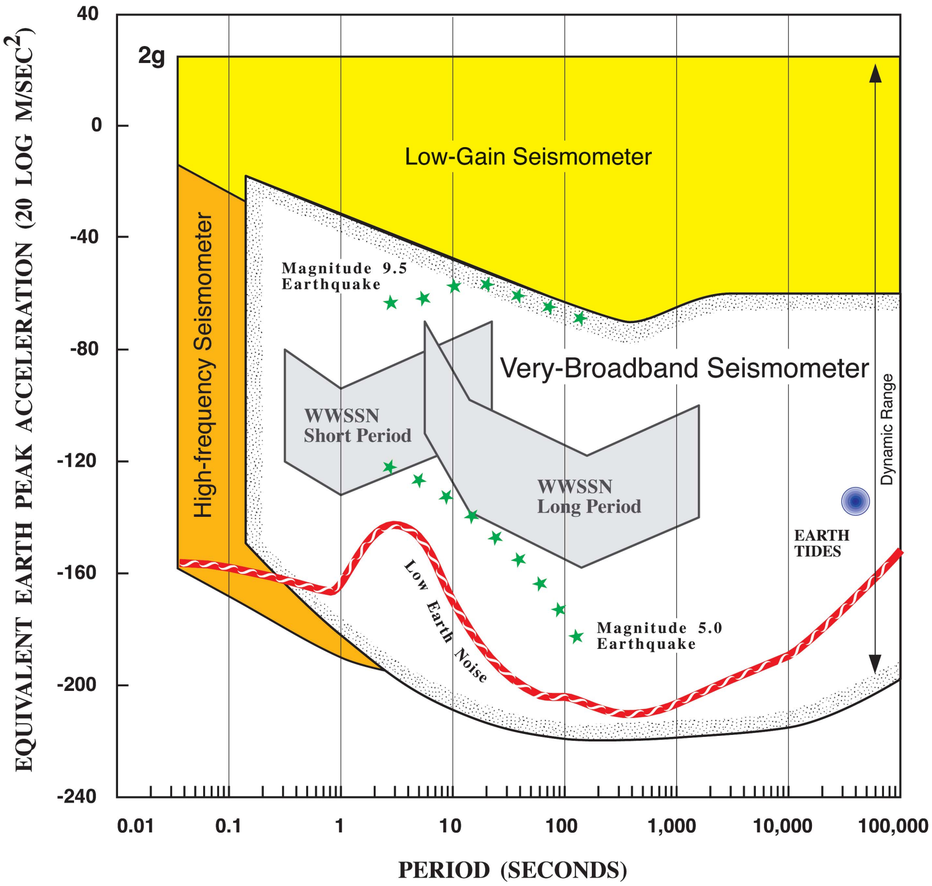

Fig. 2. The fidelity and bandwidth of the GSN system are illustrated. The approximate recording ranges of the analog WWSSN long-period and short-period channels are shown for comparison. Example ground motions from great and intermediate size earthquakes at 3300 km distance were provided by H. Kanamori, California Institute of Technology. The low Earth Noise model from Peterson *[1993] has been superseded by quieter ambient noise at selected GSN stations. The lowest and highest acceleration levels shown are for a combination of Very Broadband (Streckeisen STS-1), High Frequency Broadband, Low Gain Seismometers, and 24-bit digitizers. Although Low-Gain Seismometer response may be flat all the way to DC offset, the very large displacements implied for long-period high-acceleration motions are not achieved in normal Earth motions. (adapted from Figure 2 of* Peterson and Hutt *[1989]).*

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