The program of Congressional Science and Technology Fellows, coordinated by the AAAS and supported by most of the major science and engineering societies, came in for considerable praise during the workshop's deliberations. Science and Engineering Fellows have been an extremely valuable source of technical advice and assistance for Congress as well as the executive agencies. The program should be expanded and strengthened. In addition, a system that provides technical and analytical support to the Fellows would be a very valuable addition.

While the Congressional Research Service serves a different set of congressional needs, its analytical capabilities should be strengthened so that it can better support simple analytical requests from members and committees, which frequently involve substantial science and engineering content. Given their very different institutional cultures, it is not clear how successfully one of the existing legislative support agencies could house a new unit to perform scientific and technical policy analysis on large-scale questions that require foresight, analysis, and synthesis. However, a proposal to fund such an experiment in the General Accounting Office (GAO) only recently passed the Senate (*5*).

In today's high-tech world, legislators need balanced, nonpartisan advice and assistance if they are going to effectively serve the national interest. To make that happen, scientists and engineers, their professional societies, the business community, and individual citizens need to send a clear message to Congress. Two separate pieces of legislation that take different approaches to creating the needed analytical capability are now in progress (*3*, *5*). Others may follow. It is important that the science and technology community become actively engaged in supporting such efforts.

References and Notes

1. "Time for a bipartisan OTA," *Nature* **411**, 117 (2001).
2. The workshop, "Creating an Institutional Structure to Provide Science and Technology Advice to the U.S. Congress," was held in Washington, DC, on 14 June 2001. A summary, including agenda, list of co-convening organizations, and major insights, is available at www.epp.cmu.edu/other/STadvice_toC.html. A book based on the background papers prepared for the workshop will be published by Resources for the Future Press, Washington, DC.
3. Along with more than 30 cosponsors from both parties, Congressman Rush Holt (D–NJ) has recently introduced a simple bill, H.R. 2148, that would fund, and thus recreate, the old OTA at a level of $20 million per year for the next 6 years.
4. N. J. Vig, H. Paschen, Eds., *Parliaments and Technology: Development of Technology Assessment in Europe* (State University of New York, Albany, NY, 2000).
5. Senator Jeff Bingaman (D–NM) has successfully introduced an amendment to the Legislative Branch Appropriations Bill (S. 1172) to provide $1 million to fund a technology assessment pilot project in the GAO.

POLICY FORUM: GEOPHYSICS

The Future of Permanent Seismic Networks

Barbara Romanowicz* and Domenico Giardini

Seismologists record and analyze elastic waves produced by an earthquake to remotely determine its location and size and the orientation of the rupture plane, and to unravel the physical processes at its source. They also apply imaging techniques to infer the three-dimensional structure of Earth's interior from propagating elastic waves. These observations are done at a variety of spatial scales, from local to global, depending on the magnitude of the earthquake or the purpose of the study. Seismic data collection is also important for monitoring nuclear explosions in the framework of the Comprehensive Test-Ban Treaty (CTBT).

Observational seismology is a young science. The first seismographs that accurately recorded ground motion and time were developed 100 years ago. The first standardized global network (World Wide Standard Seismic Network, WWSSN) was deployed in the early 1960s and used analog recording on photographic paper—replaced, starting in the mid-1970s, by digital recording. Seismic practice gradually evolved from local data storage and analysis at the seismographic station to a modern database system where full waveforms are exchanged by modern media (satellite, digital phone links, or the Internet). It is only since the 1970s that the largest, globally recorded earthquakes (magnitude >5.5), have been reliably quantified, and only since the early 1980s were there sufficient recordings to systematically analyze global strain release (*1*) or to initiate global tomographic investigations of Earth's interior structure. The transition to digital seismology was largely driven by scientific rather than surveillance goals and initiated by a small number of global and regional scientific projects. More recently, a number of national programs have taken steps to install high-quality digital instruments and to upgrade the analog short-period networks to improve national earthquake surveillance.

Seismological research benefits from the availability of a broad frequency band—digital, high–dynamic range systems that can record the full "useful" range of ground-motion amplitudes and frequencies while simultaneously resolving background noise. It is no longer the quality of the data, but primarily the spatial resolution, the centralized archiving, and the continuity in time of the archives that will be critical for progress in understanding the dynamics of the solid Earth and the generation of earthquakes.

Spatial and Temporal Sampling

The imaging resolution of earthquake sources and of the lateral heterogeneity encountered by earthquake waves along their path is directly related to the spacing of the recorders at the surface. In the early 1980s, the first global tomographic investigations used 10 to 20 globally distributed digital stations, and resolved Earth's structure down to scale lengths of 5000 km, while today—at least on land—most 2000-km by 2000-km patches of Earth contain at least one digital station. Unraveling regional variations of structure, as well as earthquake location, for national monitoring requires a spacing of a few tens to a few hundreds of kilometers. Understanding the distribution of strong ground shaking in urban areas requires even denser spacing, at the kilometer level. Japan has taken the lead in the installation of dense urban arrays.

The processes that cause earthquakes have time scales of millions of years, and recurrence times of large earthquakes are typically a few hundred years in areas of plate boundaries, and up to tens of thousands of years in stable continental regions. The long-term, sustained, consistent, high-quality recording at a variety of scales is crucial to quantifying tectonic motions in Earth's crust.

For example, documenting past seismicity is the key to understanding future hazards. In California, historical earthquake catalogs cover barely over a hundred years, yet they are the basis for the computation of future earthquake probabilities and the implementation of long-term mitigation strategies. As in medical imaging, tomographic investigations of Earth's interior depend on good coverage of ray paths and

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thus on a good distribution of both receivers and sources. However, natural sources have an irregular distribution in time and space, and only continuous, long-term observation over many decades can provide adequate sampling in areas of sparse seismicity.

Accessible Data

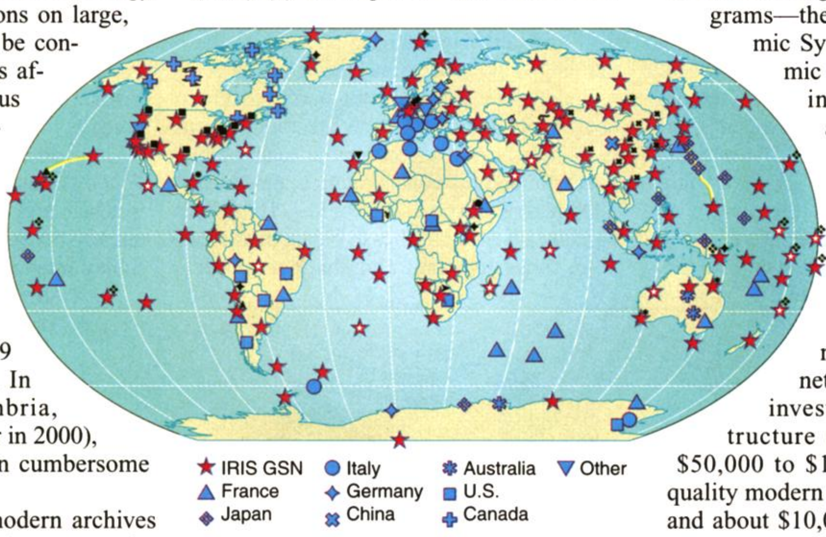
In the past 10 years, seismic research has been fostered by the increased availability of seismic waveforms, as global and national organizations strive to provide rapid access to the collected data (tens of terrabytes of compressed data archived to date). Rapid access to high-quality wave forms has become a prerequisite of modern seismology, so that detailed investigations on large, disastrous earthquakes can be conducted within a few months after the event, and continuous earthquake surveillance relies on real-time data acquisition from national and local networks. For example, Japan and Taiwan provided rapid and free access to local data recorded after the Kobe 1995 and Chi-Chi 1999 earthquakes, respectively. In other cases (such as Umbria, Italy, in 1997 or El Salvador in 2000), the access to data has been cumbersome and delayed.

It is also crucial that modern archives preserve the continuity of data access for the needs of future generations of seismologists. Structural investigations always use the longest possible data set of high-quality observations, to improve resolution, and we routinely reprocess older earthquakes with modern methodologies. For example the magnitude 7.2 earthquake that devastated Messina and Eastern Sicily in 1908, killing more than 80,000 people, was recorded by over 120 seismic analog stations worldwide. More than half of these paper records can still be retrieved today from the original observatories.

Global and Regional Networks

Unlike the WWSSN, which was developed mainly for monitoring nuclear explosions, the current-generation global network (see the figure) has been constructed with a science rationale, and significant funding from national science agencies. The Federation of Digital Seismograph Networks (FDSN) (*2*, *3*) coordinated the worldwide deployment of digital, broadband seismic instruments, organized in nationally supported and operated networks. A standard data-exchange format has emerged, and a software-based system now links the main data archives, in the United States, Europe, and Japan. The IRIS (Incorporated Research Institutions for Seismology) (*4*) Data Center in the United States provides a centralized facility for global data exchange.

The future of global seismological monitoring will require increasing the spatial resolution on land with permanent stations or temporary deployments, expanding the global coverage onto the ocean floor, and maintaining the present global network. All of this should be facilitated by strong coordination, as is being discussed between the research community and the International Monitoring System (IMS) (*5*) developed for the CTBT. However, although there is overlap, the goals of the IMS impose different requirements on instrumentation and data distribution from those of basic research.



Present distribution of global digital broadband stations contributing to the FDSN. Regional seismic networks are not shown. Open symbols indicate systems that have not yet been installed; black symbols indicate cooperative efforts. [Courtesy of Rhett Butler, IRIS]

At the regional scale, the construction of seismic networks is traditionally much more fragmented by national or state boundaries. The European example is quite striking. Driven by the national monitoring needs, there will soon be about 500 broadband stations operating in Europe, with a spatial scale of about 50 km in some areas. This density of coverage has not yet been translated into seamless, standardized, and sustained data access, as it is operated out of more than 40 different centers, sometimes with more than one in a given country. National agencies are often focused on the monitoring of their country's own seismicity and do not yet see the advantages of freely sharing data.

The collection, archiving, and distribution of broadband seismic data have been organized in Europe around the ORFEUS data center (*6*) located in the Netherlands, in step with the FDSN and its standards (*7*). ORFEUS, however, represents a small, incremental effort with respect to the large resources invested by the national agencies. Only a stronger ORFEUS, with enhanced central collection and distribution capabilities, will effectively integrate the fragmented European arrays into a regional-scale, common network.

In the United States, the situation was similar until recently, with many unconnected regional networks operating on 1960s technology. Two complementary programs—the Advanced National Seismic System (*8*), focusing on seismic hazards, and the USArray, investigating the structure and evolution of the American continent—will result in better integration of broadband networks there.

The Future

Long-term operation and maintenance of seismic networks are as expensive as investing in the initial infrastructure (it costs on the order of $50,000 to $100,000 to install a high-quality modern broadband seismic station, and about $10,000 to $50,000/year to operate and maintain it, not counting central archiving), but they are essential. National agencies need to understand that long-term gains will come not from jealously guarding seismic data as a national treasure, but from unrestricted and free data exchange. National and international agencies need to invest in coordinated centralization to mold a mosaic of heterogeneous local and regional networks into an integrated tool for earthquake surveillance and scientific research at a continental scale. As other fields of science increasingly realize the importance of sustained time series observations, it is time to consider possible synergies and develop common infrastructure to collectively build a long-term planetary-scale and cost-effective observation system.

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