Nuclear Test Ban Monitoring: New Requirements, New Resources

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Science, New Series, Vol. 263, No. 5147 (Feb. 4, 1994), 634-635.

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For decades, the United States' national security priority was to contain aggressive Soviet power. Accordingly, arms control proposals intended to limit or ban the testing of nuclear weapons were evaluated in the context of U.S.–U.S.S.R. competition, and efforts to monitor such treaties were developed mainly to constrain Soviet testing activities. The breakup of the Soviet Union and the recognition of active nuclear weapons programs in Iraq and North Korea, however, have changed all that.

Today, concern over an accelerated arms race between the superpowers (vertical proliferation) has become secondary to concern over the spread of nuclear weapons to nonnuclear states (horizontal proliferation). Consequently, the emphasis for test ban agreements is no longer on bilateral arrangements to reduce the level below which testing is allowed but rather on multilateral arrangements to ban all nuclear tests (*1*). Seismology has long provided one of the basic tools for monitoring test ban treaties. But to verify compliance with a global Comprehensive Test Ban Treaty (CTBT), we cannot simply extend the old strategy that focuses on the monitoring of known test sites down to a certain level with high confidence. Rather, we must develop a new strategy for monitoring the world and for increasing confidence that no nuclear test could go undetected. This requires a fundamental change in how we develop and apply seismological resources.

Historically, the U.S. monitoring effort focused on known testing areas within the U.S.S.R. to insure compliance principally with the 150-kiloton limit of the 1974 Threshold Test Ban Treaty (*2*). In the new geopolitics, the international community must broaden the task to detect, locate, and identify low magnitude seismic events in most regions of the globe. Accordingly, we need to expand our focus from low-frequency teleseismic waves (those that travel distances greater than 1500 km) to higher frequency regional waves (those that generally travel less than 1500 km). The new requirements for an official monitoring system, including the routine analysis of seismic events, will need to be developed within the CTBT negotiations. There is, however, a new resource developed by the scientific community that can contribute important data to the task, namely, networks of open seismic stations (Fig. 1).

Like earthquakes, underground nuclear explosions create seismic signals that travel through the Earth. For use as a monitoring tool, a seismic network must be able to both detect and identify the source of the seismic signal. Detection consists of recognizing that a seismic event has occurred and locating the source of the seismic signal. Identification involves discriminating whether the source was a nuclear explosion, an earthquake, or a chemical explosion used in industries such as mining. In addition, the monitoring system must be able to perform these tasks despite any plausible attempts to evade the monitoring system. The most problematic evasion scenario is decoupling; that is, muffling the seismic signal by detonating the explosion in a large underground cavity. Throughout the 1970s and 1980s, the verification limit for monitoring a test ban treaty was established as the yield at which it could not be demonstrated convincingly that a decoupled nuclear explosion in the Soviet Union would be detected and identified with high confidence (*3*).

Assessments of verification limits are determined not only by technical calculations, but also by judgments about what constitute reasonable assumptions about deterrance, risk, and benefits (*4*). In particular, the old assumptions appropriate for monitoring the Soviet Union in the context of a bilateral superpower treaty may not be appropriate for monitoring a global CTBT in a multipolar world.

Where the objective is to monitor the preliminary test of a first-generation nuclear weapon of simple design, the task can be readily accomplished. Such a weapon would have a likely yield of 10 kilotons or more. Decoupling for an explosion of this size is not a credible evasion scenario, and the explosion would therefore produce a seismic signal of Richter magnitude $M = 4.8$ (*5*). There are approximately 1500 earthquakes of this size each year (*6*). These events can be readily detected and identified with data from existing seismic networks.

Where the objective is to monitor a nation with an advanced secret nuclear weapons program, or a nation that may be able to obtain tactical nuclear weapons from an advanced nuclear weapon state and may want to subject one of them to a proof test, the monitoring requirements become more stringent. Such explosions could have yields of about 1 kiloton or below, and in a few locations, decoupling could be a credible evasion scenario. Without decoupling, a 1-kiloton nuclear explosion, for example, creates a seismic signal $M \approx 4.0$. There are about 7500 seismic events each year with $M \geq 4.0$. Even at this magnitude, however, there is little disagreement that all such events in continental regions could be detected and identified with current or planned networks.

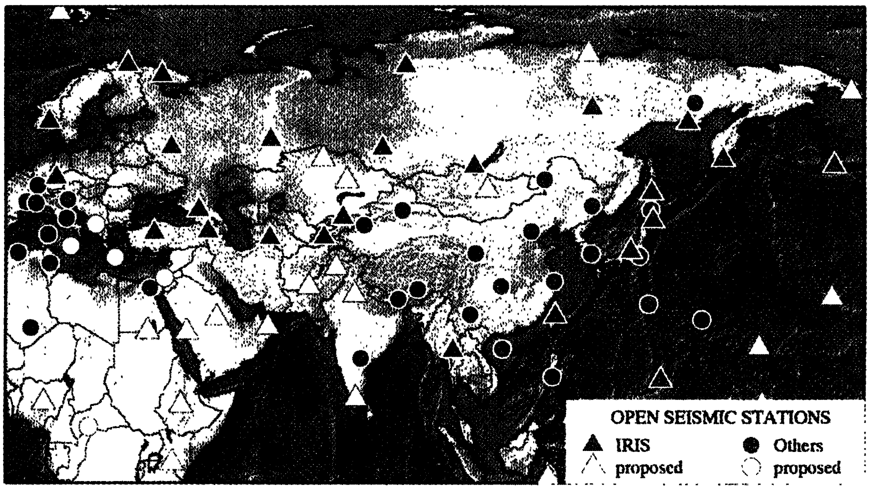

Fig. 1. Many high-quality open seismic networks are being installed around the world. Recent developments in instrumentation mean that these stations can contribute data to the full spectrum of seismic applications including earthquake activity, treaty verification, and the scientific exploration of the Earth's interior. Such multiuse stations, in conjunction with global communication networks, create opportunities for considerable cost savings and the development of a sustainable global facility for the scientific monitoring of the Earth. The current political structure of the negotiations, however, has so far prevented these networks from being incorporated into the verification effort for a proposed Comprehensive Test Ban Treaty.

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Where the objective is to monitor advanced nuclear weapon states with testing expertise and experience, such as the United States, Russia, and China, the monitoring task becomes increasingly difficult. Such countries are deemed capable of decoupling evasion. If, for example, a country were able to decouple a 1-kiloton explosion in a large underground cavity, the muffled seismic signal generated by the explosion might be equivalent to 0.015 kilotons and have a magnitude of about 2.5. Although a detection threshold of 2.5 could be achieved, there are over 100,000 events each year with $M \geq 2.5$. Even if event discrimination were 99% accurate, many events would still not be positively identified by seismic means alone. Furthermore, at this level, one must not only distinguish possible small nuclear tests from earthquakes, but also from chemical explosions used for legitimate industrial purposes. In the United States, for example, there are hundreds of chemical explosions of 10 tons or more each month (*7*).

A CTBT will be considered verifiable as long as it is judged that the benefits of the treaty outweigh the costs of any potential small undetected violations. Through a similar cost-benefit analysis, the United States and other concerned countries will have to determine the level of effort they wish to apply to monitoring small seismic events around the world. Because the number of seismic events increases exponentially with decreasing magnitude, there will probably be about a tenfold increase in cost and number of ambiguous events for each magnitude unit that the detection-identification threshold is lowered. Inevitably, because funding and personnel are limited, the overall monitoring capability will be determined largely by the extent to which all available seismic data can be used.

Global seismic monitoring has direct application not only for treaty verification, but also for the recording of earthquake activity, the assessment of seismic risk, and the scientific exploration of the Earth's interior. There need not be major distinctions between an earthquake station and a nuclear-monitoring station, thus opening opportunities for collaboration and considerable cost savings.

At present, many high-quality seismic stations are being installed around the world in the United States, France, China, Canada, Italy, Germany, Japan, and Australia mainly for earthquake monitoring and research. Data exchange from these open stations is flourishing under bilateral agreements and informal arrangements. Technical developments in communication networks allow data from many (and soon nearly all) of these stations to be accessed in near-real time (Fig. 2).

Recent schemes for monitoring a proposed CTBT have argued for a limited number of stations to trigger the collection of data from a larger global network. Such a tiered approach is now used for earthquake monitoring and is an appropriate framework for monitoring a CTBT. At present, however, many available seismological resources may be neglected. The open global networks are a cost-effective source of regional distance data to complement teleseismic data obtained from a handful of specialized seismic sensor arrays. By incorporating the networks in their entirety in the CTBT verification system, any redundancy of coverage would provide data validation and high reliability to the overall monitoring effort.

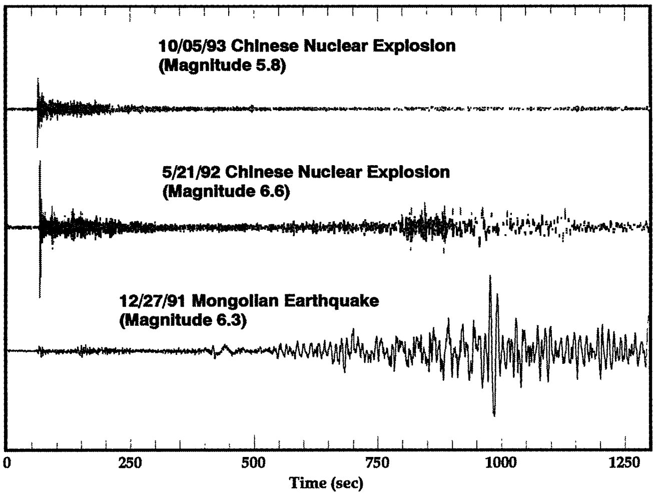

Fig. 2. Despite a multinational moratorium on the testing of nuclear weapons, China exploded a nuclear device on 5 October 1993 at their Central Asian test site at Lop Nor. The seismograms shown here, comparing the 1993 test with a larger Chinese test conducted in 1992 and a Mongolian earthquake of intermediate size, are an illustration of how technological advances and geopolitical change have assisted the global monitoring of seismicity. They were recorded at the IRIS station outside Moscow, sent over an open computer communications network in near-real time to a data collection center in California, accessed and analyzed by seismologists in Colorado and received by other researchers nationwide, all within hours of the explosion. It is now the relatively slow speed with which seismic waves travel through the Earth (a few kilometers per second) that is the limiting factor for how fast seismic data can be retrieved from around the world.

As computer communication systems continue to grow, such networks could expand into geophysical observatories with different types of sensors that contribute data not only to treaty monitoring, but to a range of scientific and environmental problems. The multiple applications of such stations will contribute to sustaining the interest and support of the host country more than specialized seismic stations whose sole purpose is for treaty monitoring. Additionally, large numbers of geoscientists will indirectly aid the treaty monitoring effort through their active use of geophysical data in related fields of research (*8*).

Although the new requirements are more extensive, the new resources combined with geopolitical changes may now allow for improvements in treaty verification beyond what was previously thought possible. Although testing is not necessarily critical to the development of a simple-design first-generation nuclear weapon, a CTBT will impede the development of advanced weapons and provide an unambiguous context in which other more direct non-proliferation efforts can be enforced. Such a CTBT, verified in part with data drawn from open seismic networks, may thus be able to deter horizontal proliferation more effectively than international agreements were able to deter vertical proliferation during the Cold War.

REFERENCES AND NOTES

1. G. E. van der Vink, *Arms Control Tod.* **20**, 18 (1990).
2. One kiloton was originally defined as the explosive equivalent of 1000 tons of TNT, later redefined to be an energy release of 10^{12} calories. The bomb dropped on Hiroshima had a yield of approximately 15 kilotons.
3. Estimates have ranged between 1 and 10 kilotons, although a consensus has been reached since the late 1980s that the limit is probably 5 kilotons or less depending on what could have been negotiated within the treaty. For discussion see U.S. Congress, Office of Technology Assessment, *Seismic Verification of Nuclear Testing Treaties* (Government Printing Office, Washington, DC, 1988).
4. In the past, verification has been a sensitive issue for the development of a CTBT. Some of the technical issues associated with verification have been misrepresented. See G. E. van der Vink and C. Paine, *Science Glob. Security* 3, 261 (1992).
5. U.S. Congress, Office of Technology Assessment, *The Containment of Underground Nuclear Explosions* (Government Printing Office, Washington, DC, 1989).
6. Based on F. Ringdal's global study of a 10-year period, for which he finds the statistical fit $\log N = 7.47 - 0.9\ M_b$ [F. Ringdal, in *The Vela Program*, A. U. Kerr, Ed. (Defense Advanced Research Projects Agency, 1985)].
7. P. G. Richards *et al.*, *Bull. Seismol. Soc. Am.* **82**, 1416 (1992).
8. A more complete discussion is in G. E. van der Vink *et al.*, *Nuclear Testing and Nonproliferation* prepared at the request of the Senate Committee on Governmental Affairs and the House Committee on Foreign Affairs of the U.S. Congress. Copies of the report are available from the IRIS Consortium.
9. Part of this work was done while G.E.V. was an International Affairs Fellow of the Council on Foreign Relations.