Policing the Peace: Verifying a Comprehensive Test Ban

"... effective verification is ... a necessary condition for a Comprehensive Test Ban Treaty. Today it does not exist. The United States has spent hundreds of millions of dollars on research to establish the basis for verifiable nuclear test limitations. The administration is continuing that search."

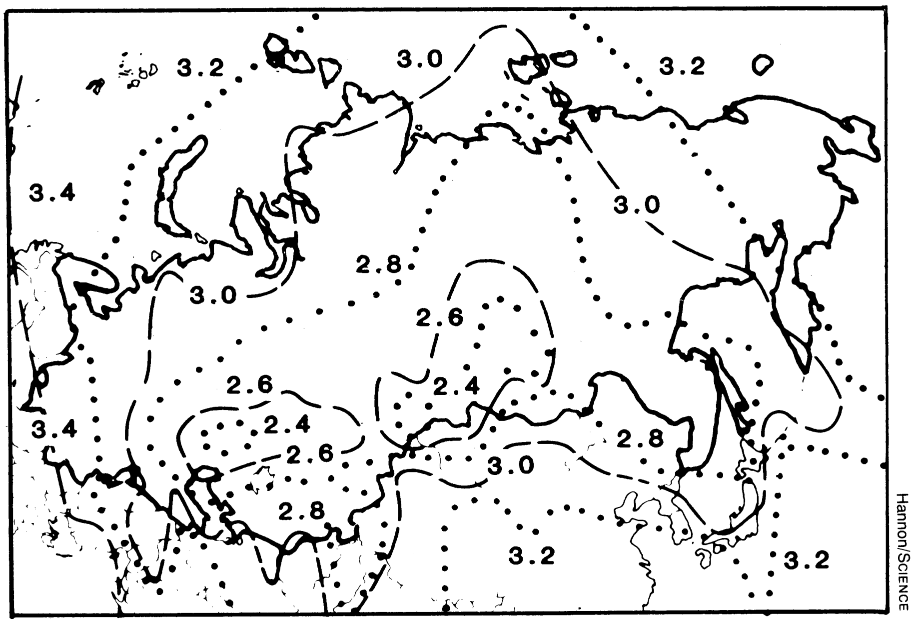
—Robert Barker,
Deputy Assistant Director for
Verification and Intelligence,
Arms Control and Disarmament Agency

"The main impediments to a CTBT are neither scientific nor technical but rest on the notion that U.S. security is best enhanced by continued testing and development of [nuclear] weapons."

—Lynn R. Sykes, seismologist,
Lamont-Doherty Geological Observatory

Second of two articles

By STEFI WEISBURD



The detection capability is calculated for a hypothetical seismic network that includes 15 small arrays placed inside the Soviet Union and 15 stations outside it. The minimum magnitudes of seismic waves that could be detected assume a 90 percent confidence level.

The hope of many arms control negotiators for the past three decades has been for a Comprehensive Test Ban Treaty (CTBT) to halt the testing of all nuclear weapons. For many years the major stumbling block in the CTBT negotiations was a disagreement about the need for each nation to place its seismic equipment inside the boundaries of the other. Many U.S. officials felt that without U.S. seismic stations inside the USSR, their ability to detect small-yield explosions in the Soviet Union would be unacceptably hampered; the Soviets, on the other hand, maintained that in-country seismic networks were not necessary for adequate verification. But by the time the last round of CTBT talks had concluded in 1980, the Soviets had agreed in principle to having in-country stations, and for many U.S. scientists verification seismology became imbued with new promise.

The recent optimism rests on the potential for monitoring high-frequency seismic signals. "It's at these very high frequencies that we might expect to see some breakthroughs in being able to look at really small shots [explosions]," says Thomas H. Jordan, a geophysicist at Massachusetts Institute of Technology.

Traditionally, verification seismologists have concentrated their studies on lower frequencies, since the high frequencies don't survive the teleseismic (greater than 2,000 kilometers) distances to which scientists had been politically constrained. Moreover, it has taken time for the digital technology to become available to efficiently monitor earthquakes at high frequencies for long time periods, notes Willard J. Hannon, a program manager of the Seismic Monitoring Research Program at Lawrence Livermore (Calif.) National Laboratory (LLNL). As a result, there are probably millions of low-frequency measurements but fewer than a couple of hundred in the high-frequency range, he says.

These high frequencies, however, may hold a key to one of the big technical obstacles to verifying a CTBT: detecting explosions that are muffled or "decoupled" below the detectable limit by placing a bomb in a large cavity, in a salt dome or in gravel. According to Hannon, an unmuffled 1 kiloton (KT) explosion, for example, might produce body waves — seismic waves that travel down through the earth's mantle and crust — with magnitudes between 3.8 and 4.2 (as determined by the geology of the USSR). The same bomb detonated in a large cavity or in gravel, on the other hand, would produce 2.2 to 2.7 magnitude waves.

Past experiments have shown that decoupling is far less effective at high frequencies than it is at lower frequencies. Although the physical mechanisms are not completely understood, seismologists explain this phenomenon using what is known as the characteristic dimension of the explosion, which is inversely related to frequency. The characteristic dimension is the distance away from an explosion at which seismic waves can propagate through rocks without permanently deforming them.

The characteristic dimension of an unmuffled explosion is relatively long; seismic signals must travel hundreds of meters before they weaken so that they no longer have the energy to melt, crack and permanently deform the rocks. The large characteristic length generates more low frequencies, just as lower-frequency sound waves are more efficiently generated by large stereo speakers. The characteristic dimension of a decoupled explosion, on the other hand, is typically much shorter; a cavity designed to decouple a 1 KT explosion would have walls that move elastically, without deforming, at only 25 meters from the explosion. As a result, for a bomb detonated in a cavity, more energy would go into the higher frequencies at the expense of the lower ones.

The possibility of monitoring high-freqency signals to detect muffled explosions may move the United States closer to a Comprehensive Test Ban Treaty, say some observers. With high frequencies, it becomes "plausible to detect these decoupled explosions no matter what the Russians try to do — which was not the case just a few years ago," says Robert R. Blandford, a program manager at the Defense Advanced Research Projects Agency (DARPA) in Arlington, Va. "But the key question at this stage, from a research point of view, is can we make use of it in a practical way for detection?"

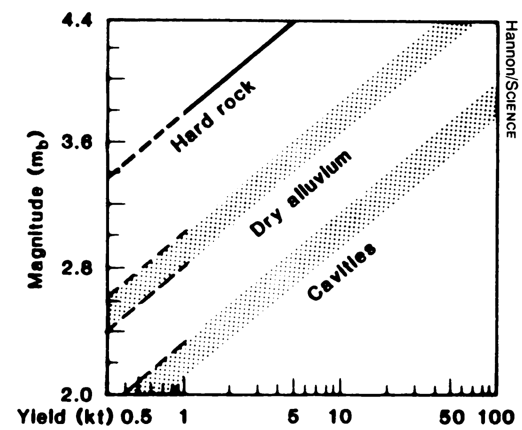
The Reagan Administration and the CTBT

Ronald Reagan is the first president since Eisenhower who has not actively negotiated a Comprehensive Test Ban Treaty (CTBT). The last round of CTBT talks with the Soviet Union and the United Kingdom actually ran aground during the Carter administration (after the Soviet invasion of Afghanistan, troubles in Iran and problems with the SALT II treaty), but it was President Reagan who officially withdrew the United States from further CTBT negotiations.

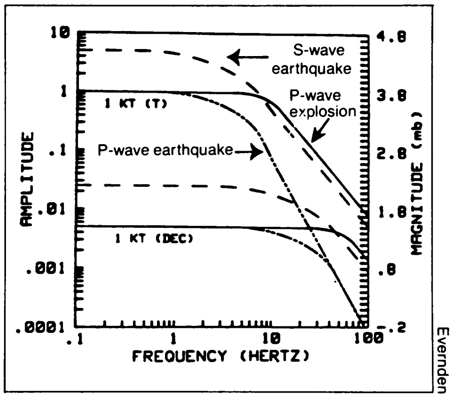
The administration maintains that a CTBT is still a long-range objective, but only in the context of "improved verification capabilities." But verification is not the only — and some would claim it is not the real — reason for the administration's reluctance to engage in CTBT talks at this time. In a written statement to the House Foreign Affairs Committee, the Arms Control and Disarmament Agency stated: "We do not agree that a test ban will reduce the risk of nuclear war. Instead it could result in instabilities that could increase this risk. Nuclear testing plays an essential role in ensuring a credible nuclear deterrent... [which] has prevented nuclear war.... And because it is not effectively verifiable, a CTB or moratorium could be violated with very destabilizing consequences."

Echoing the administration's sentiments are many scientists and administrators in weapons laboratories who have emphasized the need for testing in order to improve the efficiency, safety and materials requirements of nuclear weapons and to maintain the current stockpile. "Nuclear tests are essential for determining the proper functioning of a nuclear explosive," Donald Kerr, director of the Los Alamos (N.M.) National Laboratory, told Congress this year. "Calculations do not suffice and there is no way experimentally to simulate the total performance of a nuclear weapon."

Others have argued that without being able to test their designs, weapons scientists would lose interest in the labs, and the nuclear weapons infrastructure in the United States would disintegrate. The danger then, they say, is that the United States would be severely handicapped in the event that the Soviets violated a CTBT and resumed testing in the future. *—S. Weisburd*



Cavities and dry alluvium (gravel) can muffle, or decouple, an explosion that would otherwise produce much higher-magnitude seismic waves in hard rock. The numbers here are based on the Nevada Test Site and monitoring at 1 hertz.



Using a simple model, Evernden predicted the amplitudes and magnitudes of different seismic waves generated by earthquakes and explosions (left). The upper curve is for a tamped (T), or unmuffled, explosion, while the bottom curve represents a decoupled (DEC), or muffled, explosion. In general, explosions are expected to generate more high-frequency signals than earthquakes with the same equivalent yield at lower frequencies. Evernden and others believe this characteristic of explosions at high frequencies will help differentiate them from earthquakes at very low magnitudes.

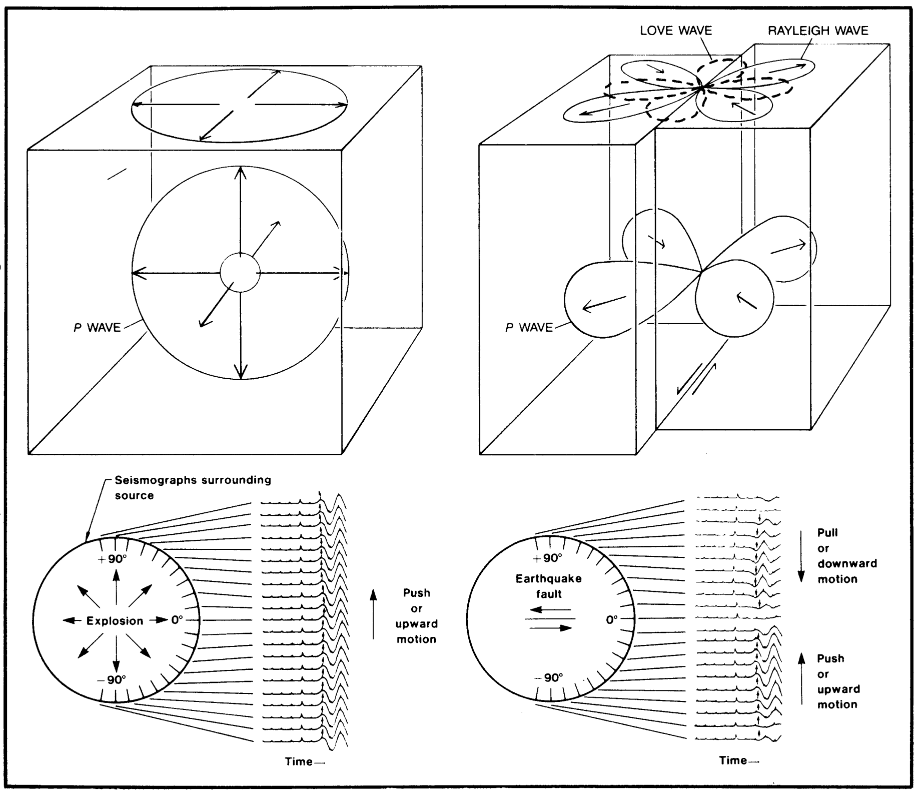
In addition to their potential for spotting decoupled explosions, high-frequency seismic networks placed in the USSR would have several other advantages. Since the sources of explosions would be relatively close, the amplitudes of all seismic waves would be larger — a help in detection efforts. Moreover, seismographs looking at a wider range of frequencies would record some types of waves that are not detectable at lower frequencies.

The potential of high frequencies has also sparked considerable debate over their use in the second step of verification: distinguishing a detected explosion from the large number of earthquakes that rattle the earth each year. At present a few different discriminants are used. For example, most of the detected events are routinely classified as earthquakes because they originate at depths greater than about 15 kilometers, which is far deeper than most drilling holes, according to Sykes and Jack F. Evernden at the U.S. Geological Survey in Menlo Park, Calif. Other events are tagged as earthquakes because of where they occur geographically.

A distinct difference between an explosion and an earthquake is that an explosion radiates energy uniformly in all directions, whereas an earthquake, created when two crustal blocks slide past one another, generates a far less symmetric pattern. As a result, an explosion tends initially to radiate mostly compressional or P (for primary, since P waves arrive at seismic stations before other body waves) body waves, which produce an upward and outward motion at the earth's surface. In contrast, earthquakes are more prolific sources of shear or S body waves as well as of surface waves.

Often, seismologists can differentiate between earthquakes and explosions by comparing the magnitude of one type of body wave (m_b) to the magnitude of one type of surface wave (M_s). For body wave values greater than 4.5, the m_b/M_s ratio is typically much lower for an earthquake than for an explosion.

For detecting and identifying small explosions at levels relevant to a CTBT or very low Threshold Test Ban, Evernden and others are enthusiastic about the use of high frequencies. A number of studies have shown that the amplitude of P waves generated by earthquakes falls off much more rapidly with increasing frequency than does the P wave amplitude from explosions. (The reasoning is that the sharp and impulsive explosions create more high frequencies than the slow, heaving motions of earthquakes.) Thus, at high frequencies, some scientists expect that most of the small events man-



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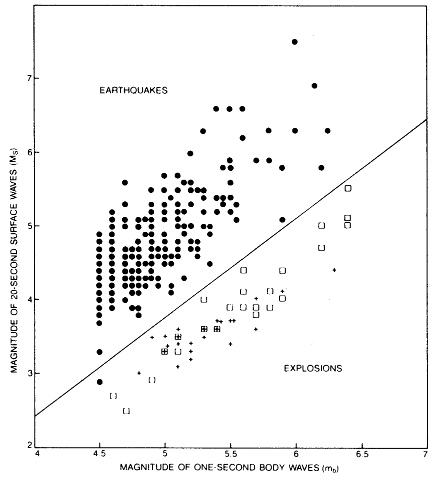
The radiation patterns of a compressional (P) wave from an underground explosion (top left) and an earthquake (top right) are very different. Because an explosion initially radiates energy uniformly in all directions, the ground motion it creates will be upward and outward regardless of the location of the seismographs recording the event (bottom left). The radiation pattern of an earthquake is not spherically symmetric like that of an explosion; the motion of P waves is inward in some directions and outward in others. Therefore, seismographs can record ground motion that is either upward and outward from the source or downward and inward toward the source, depending on where the seismic station is in relation to the fault (bottom right). The Love and Rayleigh waves in the drawing are the patterns of surface wave energy generated by this simple vertical strike-slip fault.



Sykes, Evernden, © 1982 Sci. Am. Inc.

Earthquakes can often be distinguished from explosions by comparing the magnitude of one surface wave to that of a body wave (which travels deep in the earth) generated by an event. In general, earthquakes produce more surface waves, so that the ratio of surface wave magnitude to body wave magnitude during an earthquake is greater than what would be measured during an explosion. This appears to hold true at lower magnitudes, but the bulk of evidence has been obtained for larger events. In the figure, squares denote underground U.S. explosions and crosses denote underground explosions in the USSR.

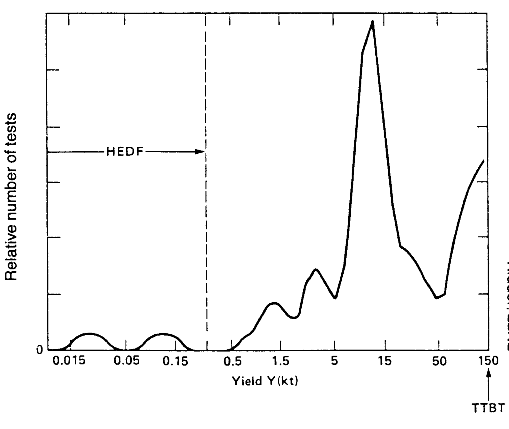
aging to rise above the noise level would be explosions. Evernden says that the theory predicting the different behavior of earthquake and explosion P waves has been supported by the analysis of hundreds of earthquakes and a number of explosions.

But other scientists are not as sanguine about this use of high frequencies as a discriminant, at least not yet. "There are cases where explosions have lower-frequency signals than earthquakes," says Blandford. "You just can't brush those off." He and others suspect that the high-frequency behavior of explosions depends strongly on the kind of geologic material in which a bomb is detonated.

There is, however, some dispute over the validity of at least one study that produced results conflicting with Evernden's ideas. "The problem is that no one has really systematically looked at earthquakes from a variety of sources around the world," says Milo D. Nordyke, program leader for the Verification Program at LLNL. "And, in fact, our data on explosions at those high frequencies are not all that good either."

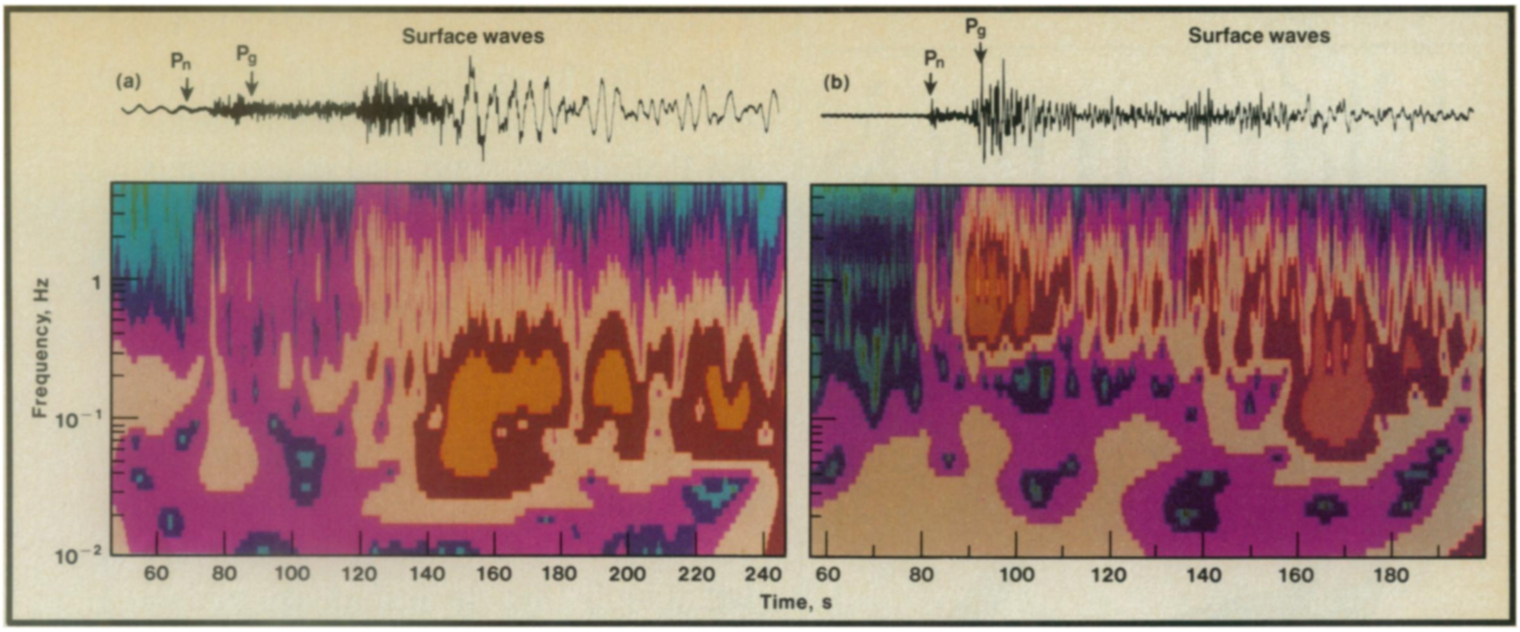
Another unresolved technical question is whether it would be possible to find recording sites in the USSR that would not be swamped with seismic noise from other sources such trains, cities and even winds.

Many of the research questions centering on high frequencies will be addressed in the next few years by NORESS (Norwegian Regional Seismic Array), an array of seismometers arranged in four concentric circles that was installed last summer about 60 miles north of Oslo. The array, sponsored by the U.S. Department of Energy and DARPA, is specially designed to monitor high frequencies. Another high-frequency array is currently being negotiated with another Nordic government. In addition to learning more about high frequencies and archiving high-



Kidder/LLNL

A Comprehensive or very low Threshold Test Ban Treaty by itself would not reduce stockpiles of existing nuclear weapons or end the arms race, but it could impinge on the development of new weapons designs. As illustrated by this graph, presented last July in Pajaro Dunes, Calif., by Ray E. Kidder of Lawrence Livermore National Laboratory (LLNL) at a Department of Energy-sponsored workshop on cavity decoupling, the military significance of tests near 10 and 150 kilotons has been far greater than that for tests below 1 kiloton under the Threshold Test Ban Treaty. Kidder predicts, however, that if the threshold were set at 1 kiloton the military would increase its testing at levels just below 1 kiloton. He also says that low-yield tests producing energy densities and states of matter comparable to those produced in nuclear explosions could have considerable indirect military value, and notes that LLNL has studied the possibility of building a High Energy Density Facility (HEDF) that could fully contain yields of up to 300 tons in order to perform these kinds of tests.



The time-evolution of an earthquake (left) as a function of energy and frequency was recorded just a few hours before an explosion (right) was detonated at the Nevada Test Site. The spectrum of colors corresponds to a range of energies—in decreasing order of energy content: yellow (most energy), red, beige, pink, dark blue, bright blue and green (least energy). Since the earthquake's magnitude 4.2 body wave was much smaller than the magnitude 5.3 explosion, the color coding for absolute energy values is not directly comparable for the two events. Nonetheless, the energy content of high frequencies is clearly greater for the explosion; between 0.5 and 2.0 hertz, for example, there is much more yellow and red between 80 and 100 seconds into the explosion than for the earthquake. Above the color graphs, seismograms demonstrate how surface waves are much more pronounced for the earthquake than for the explosion. P_n and P_g are two types of compressional body waves.

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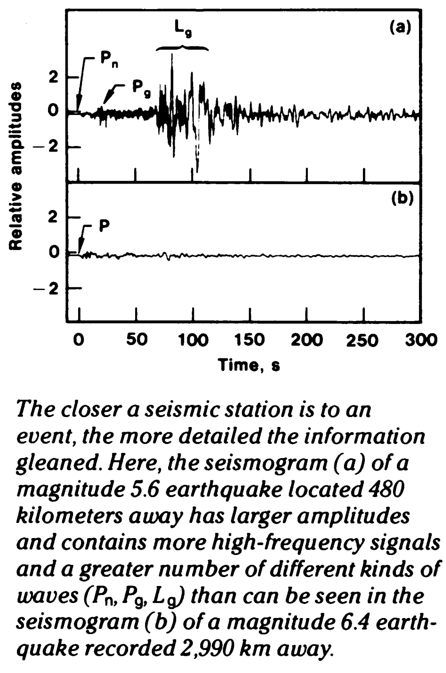
frequency data, NORESS will give scientists more experience with seismic arrays. Seismologists think that arrays will enhance their ability both to pinpoint the location of an explosion and to pull out a signal from the background wash of noise. "In general, I think you expect an array to lower the [detection] threshold by about a half a magnitude unit or so," says Nordyke.

In spite of the current uncertainties, scientists do know enough to estimate the detection capabilities of an in-country seismic network under a CTBT. Evernden, for example, thinks that a network of about 25 individual seismic stations in the USSR plus about 15 stations surrounding that country could quite easily monitor a treaty set at a 1 KT limit. In another scenario, Sykes envisions a system with modest high-frequency capabilities, including 15 in-country seismic stations that would detect explosions with fully coupled yields smaller than 0.1 KT and explosions decoupled by a salt dome or gravel with yields down to 1 KT. With no internal stations, the limit would be about 10 KT, he says. Hannon believes, as outlined in the Jan. 18 SCIENCE, that a larger network of about 30 arrays in the USSR would be needed in order to detect—with a 90 percent confidence level over 90 percent of the USSR—a magnitude 2.6 event, which is the upper end of magnitudes estimated to result from a 1 KT cavity-detonated explosion.

In general, a network's ability to detect smaller and smaller events with confi-



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The closer a seismic station is to an event, the more detailed the information gleaned. Here, the seismogram (a) of a magnitude 5.6 earthquake located 480 kilometers away has larger amplitudes and contains more high-frequency signals and a greater number of different kinds of waves (P_n, P_g, L_g) than can be seen in the seismogram (b) of a magnitude 6.4 earthquake recorded 2,990 km away.

dence increases with the number of stations, the use of arrays and other factors—all of which would have to be negotiated with the Soviets. But with improved detection capability, seismologists would also pick up a greater number of small-magnitude earthquakes and other seismic noises. This would add to the amount of data to be sorted through and would make the discrimination between explosions and earthquakes that much more critical. Some scientists add, however, that discrimination would improve dramatically if high-frequency data were used.

Besides small earthquakes, a potentially serious problem for a CTBT or a low Threshold Test Ban Treaty would be quarry blasts and other chemical explosions set off in huge numbers every year in both the United States and the Soviet Union. According to Hannon, typical chemical blasts measure about 20 tons but can have yields as high as 4 KT. Scientists have yet to find any seismic means of adequately distinguishing between chemical and nuclear explosions in that range. But if no technical solutions are found, observers say, nontechnical agreements, such as announcing blasts before they occur, could be negotiated.

Many seismologists feel they are in a considerably better position today to gauge both the promise and the limits of seismic verification. When scientists first approached the verification problem decades ago, says Jordan, seismology lost credibility in the eyes of the Defense Department and other government agencies because the seismologists were just getting their feet on the ground. But now, many seismologists believe they have a much better handle on what they consider the best verification technique — seismic monitoring. And some of these scientists feel that one of their greatest challenges today is to reestablish the credibility of seismology in government circles so that the science is fairly considered in political questions. □