Chapter 4

Detecting Seismic Events

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Chapter 4
Detecting Seismic Events

The first requirement for a seismic monitoring network is to detect and locate seismic events that could have been caused by an underground nuclear explosion.

INTRODUCTION

The first requirement for a seismic monitoring network is that it be capable of detecting seismic events. If the Earth were perfectly quiet, this would be easy. Modern seismometers are highly sophisticated and can detect remarkably small motions. However, processes such as the winds, ocean waves, and even rush hour traffic continually shake the Earth. All of this ground movement is sensed by seismometers and creates a background from which signals must be recognized. Seismic networks, consisting of groups of instruments, are designed to detect events like earthquakes and distinguish them from normal background noise. The extent to which a seismic network is capable of detecting events, referred to as the network's detection threshold, is dependent on many factors. Of particular importance are the types of seismic stations used, the number and distribution of the stations, and the amount of background noise at the station locations. This chapter reviews these factors and discusses the capability of networks to detect seismic events within the Soviet Union.

THE MEANING OF "DETECTION"

In practical terms, detecting a seismic event means more than observing a signal above the noise level at one station. There must be enough observations (generally from more than one station) to estimate the location of the event that created the detected signal. Measurements of the seismic waves' amplitudes and arrival times must be combined according to standard analytical techniques to give the location and origin time of the event that generated the signal. The event could be any of several natural or man-made phenomena, such as earthquakes, nuclear or chemical explosions, meteorite impacts, volcanic eruptions, or rock bursts.

The seismic signals from these *events* travel from their *source* to individual seismic recording stations along different pathways through anon-uniform Earth. Consequently, no two signals recorded at separate stations will be identical. Even if they came from the same source, the amplitudes, shape, and transit times of the signals would vary according to the path they took through the Earth. This fact has an important impact on the results of the calculations used to determine magnitude and location. The results will never have perfect precision. They will be based on averages and will have associated with them statements of what the possible errors in the most probable solution might be. Origin times and locations of seismic events, the parameters that make up a "detection, " are always based on some averaging of the data from individual stations. To determine the origin time, and location of a seismic event, the data from several stations must be brought together at a single place to carry out the required analysis. Seismic stations that routinely send their data to a central location for analysis are said to form a *network*.

The energy radiating from an underground nuclear explosion expands outward. While most of the explosive energy is dissipated by crushing and melting the surrounding rock, a

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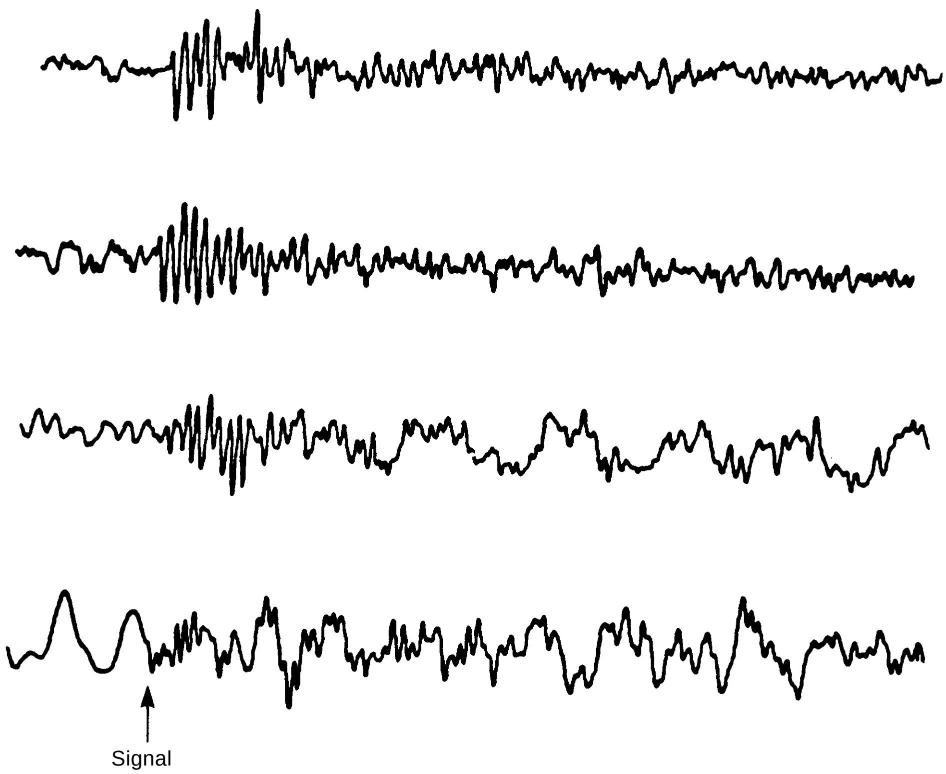
small fraction is transformed into seismic waves. These seismic waves propagate outward and, in so doing, encounter various boundaries and rock layers both at the surface and deep within the Earth. The boundaries cause a separation of the seismic waves into a variety of wave types, some of which travel deep through the interior of the Earth (body waves) and some of which travel along the surface (surface waves). See chapter 3 for a full discussion of wave types and travel paths.

Seismic signals are detected when they are sufficiently above the background noise in some frequency band. Figure 4-1 shows seismograms with standard filters designed to enhance the detection of distant events. In this case, the signal can be seen because it is larger than the noise at high frequency. When data are in digital form (as they are in the latest generation of seismic instrumentation), filters are applied in various frequency bands before detection processing.

Relatively sophisticated techniques can now be used to detect a seismic signal in the presence of noise. In those cases where three perpendicular components of ground motion are recorded using a vertical and two horizontal component seismometers, use can also be made of the known particle motion of P waves to differentiate a P wave signal from background noise. Another technique which can enhance the probability of detecting a signal requires a number of closely spaced seismic sensors known as an array. The data recorded by these sensors can be summed together in a manner which takes account of the expected signal propagation time across the array. The array enhances signals from great distance that prop-

Figure 4-1.—Seismic Signals



Small seismic signals in the presence of seismic noise at four different stations.

SOURCE: U.S. Geological Survey.

agate vertically through the array and can reject noise that travels horizontally. Therefore, the array summation process tends to enhance the signal and to reduce the noise.

For many years, most seismic verification efforts in the United States concentrated on the use of *teleseismic signals*. Teleseismic *signals* are seismic waves which travel to distances greater than 2,000 km and go deep through the interior of the Earth. Teleseismic waves are used because all seismometers monitoring Soviet testing are located outside the U.S.S.R. and generally at distances which are teleseismic to the Soviet test sites. The possibility of establishing U.S. seismic stations within the U. S. S. R., close to Soviet nuclear testing areas, was discussed seriously as part of negotiations for a Comprehensive Test Ban Treaty. Because techniques for monitoring explosions with regional signals were not as well understood as techniques for monitoring with teleseismic data, research efforts to improve regional monitoring greatly increased during the late 1970s. Regional distances are defined to be less than 2,000 kilometers and waves propagating to this distance travel almost entirely through the Earth's outer crustal layers.

LOCATING SEISMIC EVENTS

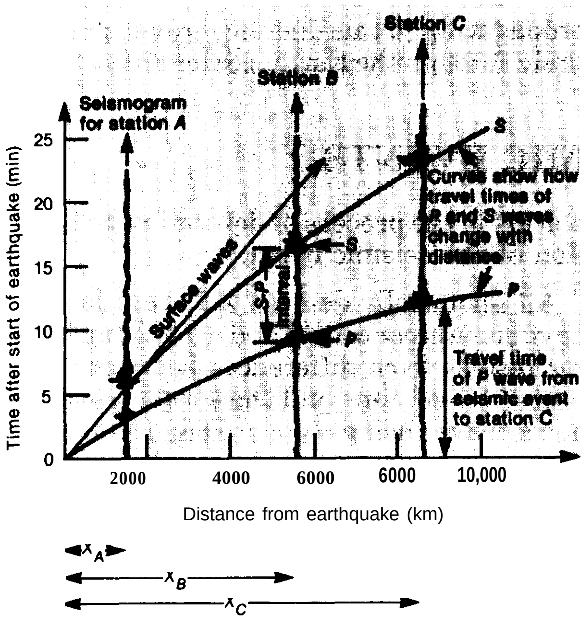
The procedure for estimating the location of a seismic event, using seismic data, involves determining four numbers: the latitude and longitude of the event location, the event depth, and the event origin time. Determination of these four numbers requires at least four separate measurements from the observed seismic signals. These values are usually taken as the arrival time of the P wave at four or more different seismic stations. In some cases, however, determination of the numbers can be accomplished with only two stations by using the arrival times of two separate seismic waves at each station and by using a measure of the direction of the arriving signal at each station. A relatively poor estimate of location can also be obtained using data from only a single array.

The event location process is an iterative one in which one compares calculated arrival times (based on empirical travel-time curves) with the observed arrival times. The differences between calculated and observed arrival times are minimized to the extent possible for each station in the process of determining the location of the seismic event.

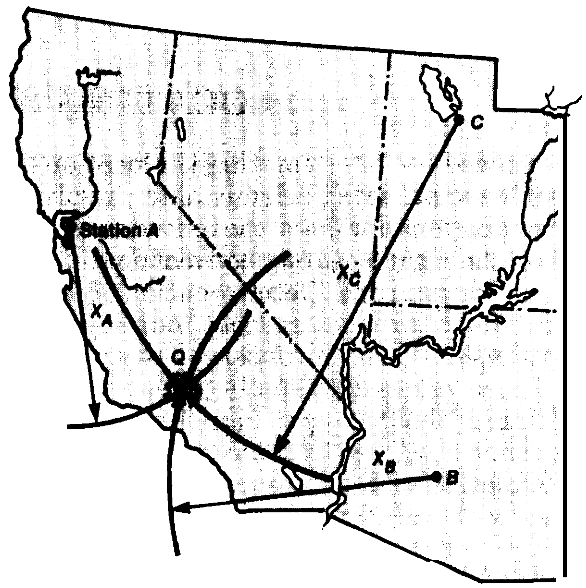
All seismically determined event locations have some error associated with them. The error results from differences between the expected travel time and the actual travel time of the waves being measured and from imprecision in the actual measurements. Generally, these errors are smallest for the P wave (the first signal to arrive), and this is why the capability to detect P waves is emphasized. Location errors are computed as part of the location estimation process, and they are usually represented as an ellipse within which the event is expected to be. Generally, this computation is made in such a way that there is a 95 percent probability that the seismic event occurred within the area of the error ellipse. Thus, location capability estimates are usually given by specifying the size of this error ellipse. Similarly, there is always an uncertainty associated with the measured depth of the event beneath the Earth's surface.

Box 4-A.—Locating A Seismic Event

Estimating the location of a seismic event can be compared to deducing the distance to a lightning bolt by timing the interval between the arrival of the flash and the arrival of the sound of the thunder. As an example, consider the use of the P wave and S wave, where the flash is the first-arriving P wave and the thunder is the slower traveling S wave. The time interval between the arrival of the P wave and the arrival of the S wave (which travels at about half the speed of the P wave), increases with distance. By measuring the time between these two arrivals and knowing the different speeds the two waves travel, the distance from the event to the seismometer could be determined (figure A). Knowing the distance from several stations allows the location to be pinpointed (figure B).



The time required for P, S, and surface waves to travel a given distance can be represented by curves on a graph of travel time against distance over the surface. To locate an earthquake the time interval observed at a given station is matched against the travel-time curves for *P* and S waves until the distance is found at which the separation between the curves agrees with the observed *P-S* time difference. Knowing the distance from the three stations, *A, B,* and C, one can locate the epicenter as in figure B.



Knowing the distance, say X_A, of an earthquake from a given station, as by the method Figure A, one can say only that the earthquake lies on a circle of radius *A,* centered on the station. If, however, one also knows the distances from two additional stations *B* and C, the three circles centered on the three stations, with radii X_A, X_B, Xc, intersect uniquely at the point Q, the location of the seismic event.

SOURCE: This example is taken from Frank Press and Raymond Seiver, *Earth (San* Francisco, CA: W. H. Freeman and Company, San Francisco, CA, **1974).**

DEFINING MONITORING CAPABILITY

Seismic Magnitude

A seismic monitoring system must be able to detect the occurrence of an explosion, to locate the explosion, to identify the explosion, and to estimate the yield of the explosion. The capability of a seismic network to perform each of these tasks is generally described as a function of a measure-called the *seismic magnitude* of an event.

Seismic magnitude was first developed as a means for describing the strength of an earthquake by measuring the motion recorded on a seismometer. To make sure that the measurement was uniform, a standard method was needed. The original calculation procedure was developed in the 1930s by Charles F. Richter, who defined local magnitude, ML, as the logarithm (to the base 10) of the maximum amplitude (in micrometers) of seismic waves observed on a Wood-Andersen torsion seismograph at a distance of 100 kilometers (60 miles) from the earthquake.

Subsequently, the definition of seismic magnitude has been extended, so that the measurement can be made using different types of seismic waves and at any distance. For body waves, the equation for seismic magnitude m_b is:

$$m_b = \log (A/T) + B(d,h),$$

where A is the maximurn vertical displacement of the ground during the first few seconds of the P wave, and T is the period of the P wave. The B term is a correction term used to compensate for variations in the distance (d) between the seismic event and the recording station and the depth (h) of the seismic event. For a seismic event at the surface of the Earth, h=0. The B correction term has been determined as a function of d and h by observing seismic signals from a large number of earthquakes.

For surface waves, seismic magnitude M_s can be calculated by a similar equation:

$$M_s = \log (A/T) + b \log d + c,$$

where b and c are numbers determined from experience. A number of formulas, involving slightly different values of b and c for M_s, have been proposed.

The terms in both the body wave and surface wave magnitude equations that are used to compensate for distance reflect an important physical phenomenon associated with seismic wave propagate. This phenomenon, referred to as attenuation, can be simply stated as follows: *the greater the distance any particular seismic wave travels, the smaller the wave amplitude generally becomes. Attenuation* of wave amplitude occurs for a number of reasons including:

1. the spreading of the wave front over a greater area, thereby reducing the energy at any one point on the wavefront;
2. the dissipation of energy through natural absorption processes; and
3. energy redirection through diffraction, refraction, reflection and scattering of the wave at various boundaries and layers within the Earth.

As a consequence, a correction term is needed to obtain the same magnitude measurement for a given seismic event from data taken at any seismic station. The correction term increases the amplitude measurement to compensate exactly for the amplitude decrease caused by the different attenuation factors.

Therefore, if the amplitude of the seismic wave is to be used to estimate the size of the seismic event (whether it is an explosion or a naturally occurring earthquake), a good understanding of how amplitude decreases with distance is needed for both body and surface waves. The distance-dependent numbers in the body and surface wave equations represent average corrections which have been developed from many observations. In general, these corrections will not be exact for any one particular path from a particular seismic event to a particular sensor. It is important, therefore, either to calibrate the site to receiver path or to compute the magnitude of the event using seismic signals recorded at a number of well-calibrated stations. If multiple stations are used, the event magnitude is calculated by averaging the individual station magnitudes for an event. From this procedure, an *average* body wave magnitude (rob) and an *average* surface wave magnitude (M_s are determined for the event.

Obviously, the distance the wave has traveled must be known to determine the attenuation in amplitude and correct for it. Therefore the seismic event must be located before its magnitude can be determined.

Converting Magnitude to Explosive Yield

The detection and identification capabilities of seismic networks are described most conveniently in terms of seismic magnitudes, typically m_b. This measure is used because m_b is directly related to seismic signal strength. When interpreting capabilities in terms of explosive yield, however, an additional step is required to translate m_b to kilotons. The same magnitude value can correspond to yields that range over a factor of about 10. Variations in the magnitude-yield relationship are caused by variations in the structure of the Earth in the vicinity of the test site (low signal attenuation versus high signal attenuation areas), the material in which the explosion is emplaced (hard, water-saturated rock versus dry, porous materials), and the way in which the explosion is emplaced (tamped versus detonated in a large cavity designed to muffle the signal).

For example, if an explosion is "well-coupled," that is, if the energy is well transmitted from the explosion to the surrounding rock, an m_b of 4.0 corresponds to an explosion of about 1 kt. This relationship is true only for explosions in hard rock and may vary considerably depending on how well the seismic waves are transmitted through the area's geology. In areas that are geologically old and stable, seismic waves are transmitted more efficiently. An m_b of 4.0 produced by a well-coupled explosion in an area of good transmission might correspond to an explosion much smaller than a kt. In areas that are geologically young and active, seismic waves are not transmitted as efficiently and an m_b of 4.0 may correspond to a well-coupled explosion larger than 1 kt.

Even greater changes in the relationship between m_b and yield can occur if the explosion is intentionally "de-coupled" from the surrounding rock in a deliberate attempt to muffle the seismic signal. As we will see in chapter 6, decoupling can be accomplished at low yields under some situations by detonating the blast in a large underground cavity. Through such evasion methods, the same 1 kt explosion that produced a magnitude m_b of 4.0 when "well-coupled" might be muffled down to a seismic signal of around m_b 2.() at low frequencies. Lesser reductions can be accomplished by detonating the explosion in dry porous material.

Because the yield that corresponds to a specific m_b depends so much on the scenario that is being discussed, seismologists generally use seismic magnitude to describe monitoring capabilities. In translating seismic magnitudes to yields, the reader must consider the context in which the comparison is made. In particular, it should be considered whether the explosion is being recorded in an area of good transmission and whether the explosion is well-coupled. Unless specifically stated, this report translates seismic magnitudes to yields corresponding to "tamped" conditions, that is, a well-coupled explosion in hard rock. Situations where decoupling is feasible, and the effects of such decoupling, are discussed in chapter 6.

Seismic Monitoring in Probabilistic Terms

Whether seismic measurements are made by hand or by computer, some error is involved. Even greater additional errors arise from the imperfect estimates of how well seismic waves travel through different parts of the Earth and how well seismic energy is coupled to the Earth during the explosion. All of these errors result in some uncertainty in the final determined parameters. This is true whether these parameters are event magnitude, location, identification characteristics, or yield. In all cases, however, it is possible to estimate a confidence factor in probability terms for the determined parameter. It is important to realize, therefore, that while the numbers are not presented with 100 percent certainty, estimates of the uncertainty are known. In general, this uncertainty is greatest for the small events and decreases for the larger events. A discussion of the uncertainty and what it means in terms of national security concerns is presented in chapter 2.

LIMITATIONS TO SEISMIC MONITORING CAPABILITY

The strength of a seismic signal diminishes with distance. In general, the closer the seismic station is to the source, the stronger the signal will be. Hence, a principal element of monitoring strategy is to get close to areas of concern. It follows that the more high quality stations distributed throughout a given area, the greater the capability will be to detect small events.

Seismic Noise

As noted previously, if the Earth were perfectly still, detecting even the smallest seismic event would be easy. However, the Earth's surface is in constant motion. This motion is the result of many different energy sources. Major storms over ocean areas and the resultant wave action on continental shores cause significant noise in the 2- to 8-second band. Wind noise and noise from atmospheric pressure fronts are particularly prominent on horizontal-component seismic recordings. These more or less continuous motions of the Earth are referred to as seismic *noise* or *microseisms* (figure 4-2). For purposes of siting a seismic station, it is highly desirable to find an area that has a low background level of seismic noise. Generally, the lower the background seismic noise at any station, the smaller will be the seismic signal which can be detected at that station.

Cultural activities can also generate seismic noise that appears in the frequency range used to monitor nuclear explosions. Generally, this man-made noise has frequencies higher than 1 Hz. Heavy machinery, motors, pumping stations, and mills can all generate observable seismic noise. However, careful siting of seismic stations can minimize the problem of most man-made seismic noise. From a monitoring point of view, it is important that noise surveys be made prior to the final selection of sites for seismic stations. If such sites are negotiated within other countries, provisions should be made for relocating the sites should seismic noise conditions change.

Seismic signals and noise are concentrated in various frequency bands. Only the noise within the frequency bands in which seismic signals are observed is a problem. Even strong noise can be eliminated by filtering as long as the noise is outside the detection bands of interest.

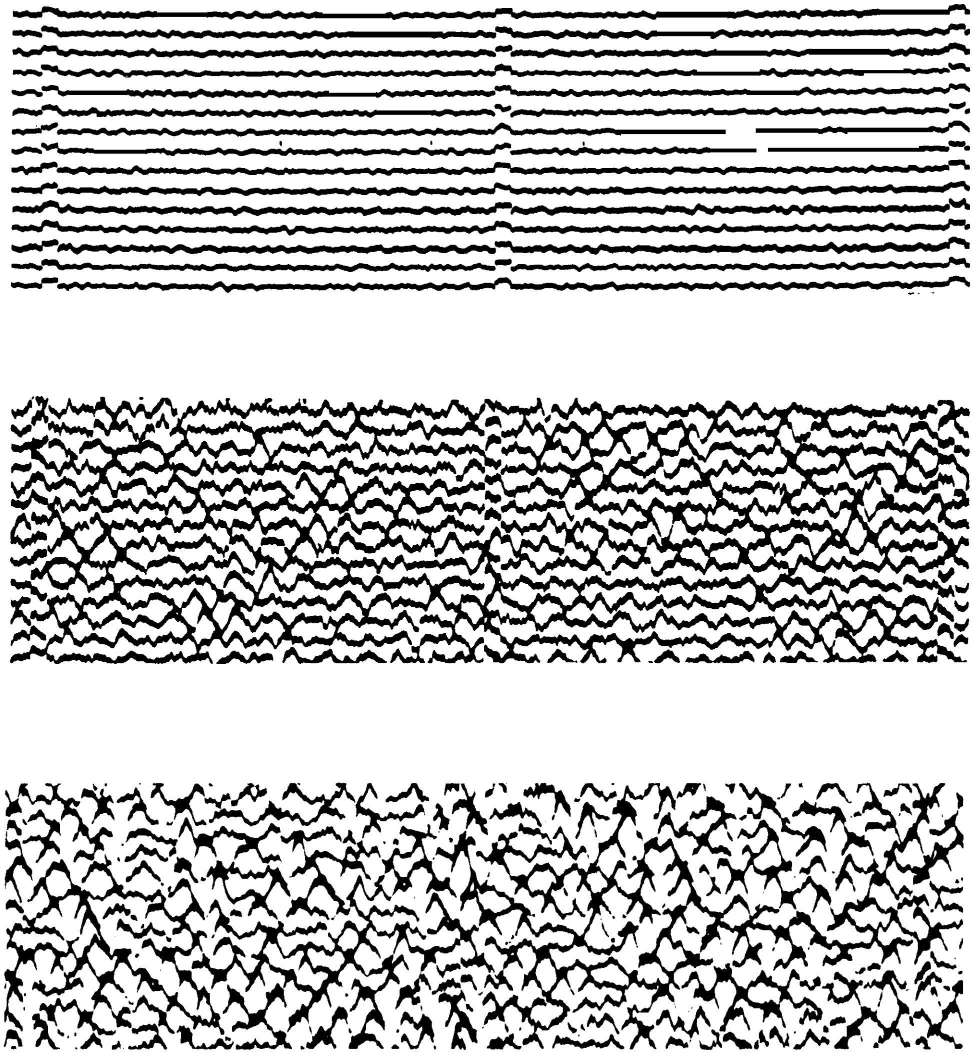
The possibility also exists that a seismic signal from one event can be masked by the seismic signal from another event. While this does indeed happen, it is only a problem for monitoring at yields around 1 kt or less without internal stations. For events of interest in the U.S.S.R. above a magnitude of about m_b 4.0, there are a sufficient number of stations detecting the event so that masking of the signal at a couple of stations generally poses no serious problem. For events much below m_b 4.0, a number of stations at regional distances (distances less than about 2,000 km) would have to be used to avoid the masking problem. Such stations would be available if the United States obtains access to data from seismic stations placed within the U.S.S.R. as part of a negotiated agreement between the United States and the Soviet Union.

Reduction of Signals at Source or Sensor

Poor coupling to the geologic media, either at the explosion source or at the seismic sensor, will act to reduce the amplitude of the seismic signal received. If the explosion is in dense hard rock or in water saturated rock, the source coupling will be good. If the explosion is in alluvium, dry porous rock, or within a cavity, the coupling will not be as good. Decoupling an explosion by detonation within a cavity is an important evasion scenario which will be discussed in chapter 6.

At the seismic sensor, signal reduction can occur if the sensor is not placed on hard rock. In particular, if there is a layer of soil upon which the sensor sits, the signal-to-noise ratio at the sensor can be far less than if the sensor

Figure 4-2.—Seismic Noise



Background seismic noise at three different stations.

SOURCE: U.S. Geological Survey.

were placed on or within hard rock. Sensors placed in boreholes in hard rock provide superior coupling to the Earth and also provide a more stable environment for the instrument packages, with a concomitant reduction in noise.

Seismic Instrumentation

Until recently, the instrumentation that was available for detecting, digitizing, and recording seismic signals did not have the capability to record all the signal frequencies of interest with sufficient range. Further, the mechanical and electronic components comprising seismic recording systems generate internal noise, which is recorded along with true ground noise and seismic event signals, and this internal noise was the limiting factor in recording seismic signals in the high frequency range. Specifically, the internal noise of the older designs of high frequency seismic detectors was higher than ground noise at frequencies above about 5 Hz. Thus, while ground noise is now known to decrease with increasing frequency, the system noise remained constant or increased with increasing frequency in the older systems. Therefore, trade-offs were made, and the entire frequency range of the signal was generally not recorded. Specifically, in the high frequency range data was generally not recorded above 10 Hz and even then was highly contaminated in the 5-10 Hz range by internal system noise. Consequently, small seismic events, particularly small explosions, with expected maximum signal energy in the high frequency range above 5 Hz were not detected because their high frequency signals were below the internal system noise levels. Most existing seismic stations are of this type and so are limited for nuclear test monitoring.

Today, broadband systems capable of recording the entire frequency range with a large dynamic range and with low internal noise are available. However, the best high performance systems are not widely distributed. To establish confident detection-identification capabilities using high frequency seismic signals at low event magnitudes, it will be necessary to expand the number of high performance stations and to place them in diverse geologic environments in order to simulate the requirements of in-country monitoring.

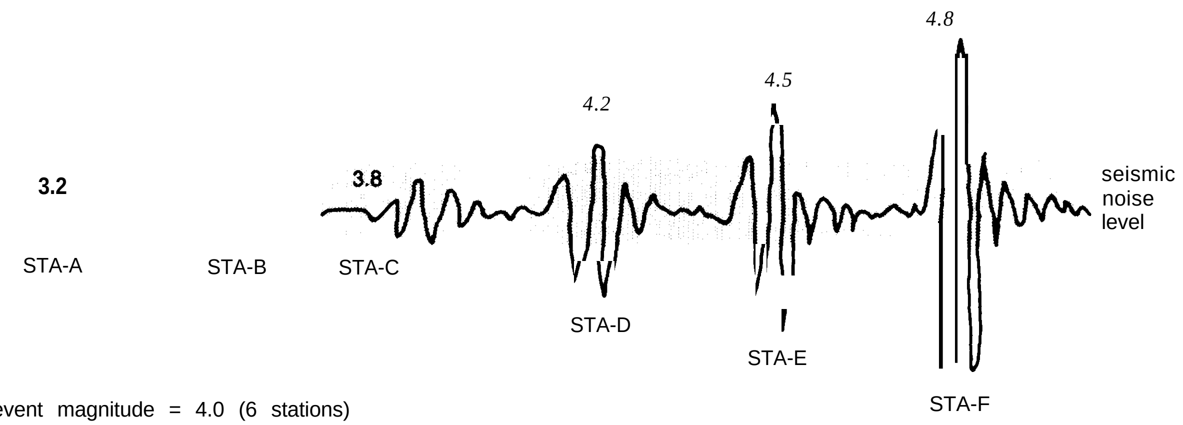
Seismic Magnitude Estimation Problems

As discussed earlier, the estimate of an event's seismic magnitude is made by combining the estimates obtained from many single stations in an averaging procedure to reduce random errors. This procedure works well for an event which is neither too small nor too large.

For a small event, however, the averaging procedure can result in a network magnitude value which is biased high. This follows from the fact that for a small event, the signals will be small. At those stations where signals fall below the noise, the small signal amplitudes will not be seen. Consequently, only higher amplitude values from other stations are available for use in computing the network average. With the low values missing, this network average is biased high unless a statistical correction is made.

Figure 4-3 illustrates this effect. All six stations (A through F) record the same magnitude 4 event. Stations A, B, and C record the

Figure 4-3.—Effect of Noise on Event Magnitude Computation



Average event magnitude = 4.0 (6 stations)

Computed average magnitude = 4.5 (3 stations)

SOURCE: Modified from Air Force Technical Applications Center.

event below average. Stations D, E, and F record the event above average. Normally, the stations would all average out to a magnitude 4.0. For a small event, however, the stations that record low (A, B, &C) do not record the signal because it is below the noise level. Only the stations that record higher (D, E, & F) show the event. Without the values from the low stations, the calculation of the average is made using only the stations that record high. The resulting calculation biases the average to the values of the higher stations, giving a false average magnitude value of (in this example) 4.5 for a 4.0 seismic event.

In the past, computed magnitudes of small events were systematically biased high in this manner. As a result, for most of the last 25 years, the U.S. capability to detect seismic events within the U.S.S.R. has, in fact, been significantly better than the estimates of this capability. Not until the late 1970s was it demonstrated that the small events being detected were 0.2 to 0.4 magnitude units smaller than previously thought. In terms of yield, this means that the networks were actually capable of detecting events down to half as large as previously thought possible. Within the last few years, analysis procedures have been employed to correct for most of this bias using a procedure called *maximum likelihood estimation.*

For large events, a similar bias problem used to exist occasionally, but for a different reason. Old seismometers could not record very large signals without clipping the signal. Larger amplitude signals were either not available or were under estimated. The resulting bias of large events, however, did not affect estimates of detection capability and only became a problem in the determination of the size of very large events.

SEISMIC NETWORKS

Existing Networks and Arrays

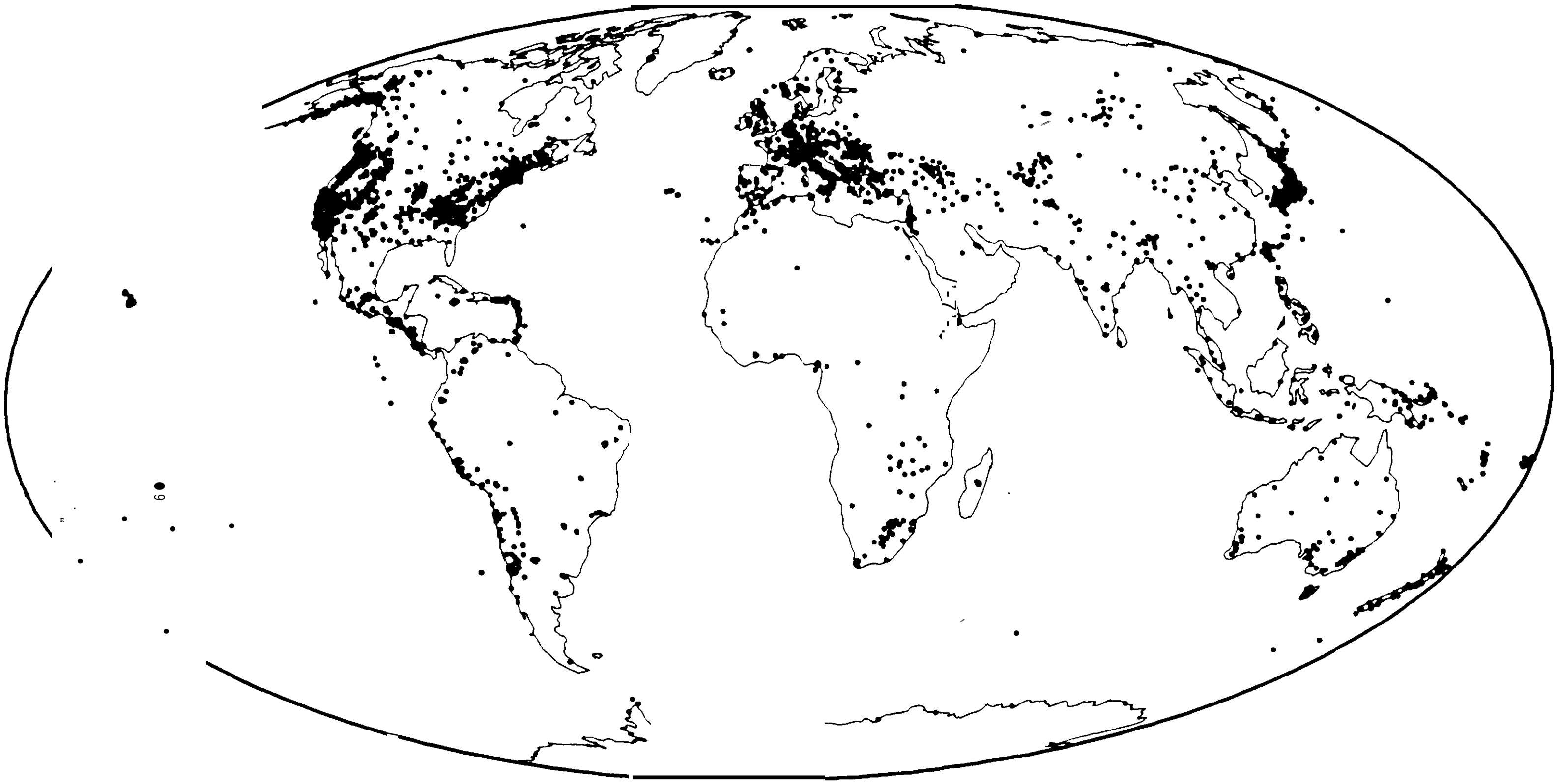
Although many thousands of seismic stations exist around the world, the actual number of stations which routinely report data to national and international data centers is a few thousand. For example, in figure 4-4 the 3,500 stations are shown that routinely report data to the National Earthquake Information Center (NEIC), a center in Colorado operated by the United States Geological Survey. Some of these stations report much more often than do others. The instrumentation at these stations is diverse and the quality of the data varied. While these stations are very useful for seismic signal detection, they are less useful for purposes of magnitude estimation and for research requiring stations evenly distributed around the world.

For purposes of treaty monitoring operations and research, a well distributed network with a common set of instrumentation at all stations is most useful. To obtain such a standard network, the United States funded the development and deployment of the Worldwide Standardized Seismograph Network (WWSSN) in the early 1960s (figure 4-5). The WWSSN is maintained by the United States Geological Survey (USGS). The quality and performance of the WWSSN is generally very good, but the recording system is limited in dynamic range and resolution because of the use of what is now obsolete analog equipment and also because of high internal noise in the amplifying equipment. (For example, the data are currently recorded only on photographic paper records.)

Beginning in the early 1970s, digital recording seismic stations were developed by the United States and other countries. The data from these stations can be easily processed by digital computers to enhance the signal-to-noise for signal detection and to analyze the data for seismic source determination and for research purposes. These stations are included in such networks as:

- The Regional Seismic Test Network (RSTN). These are high quality stations

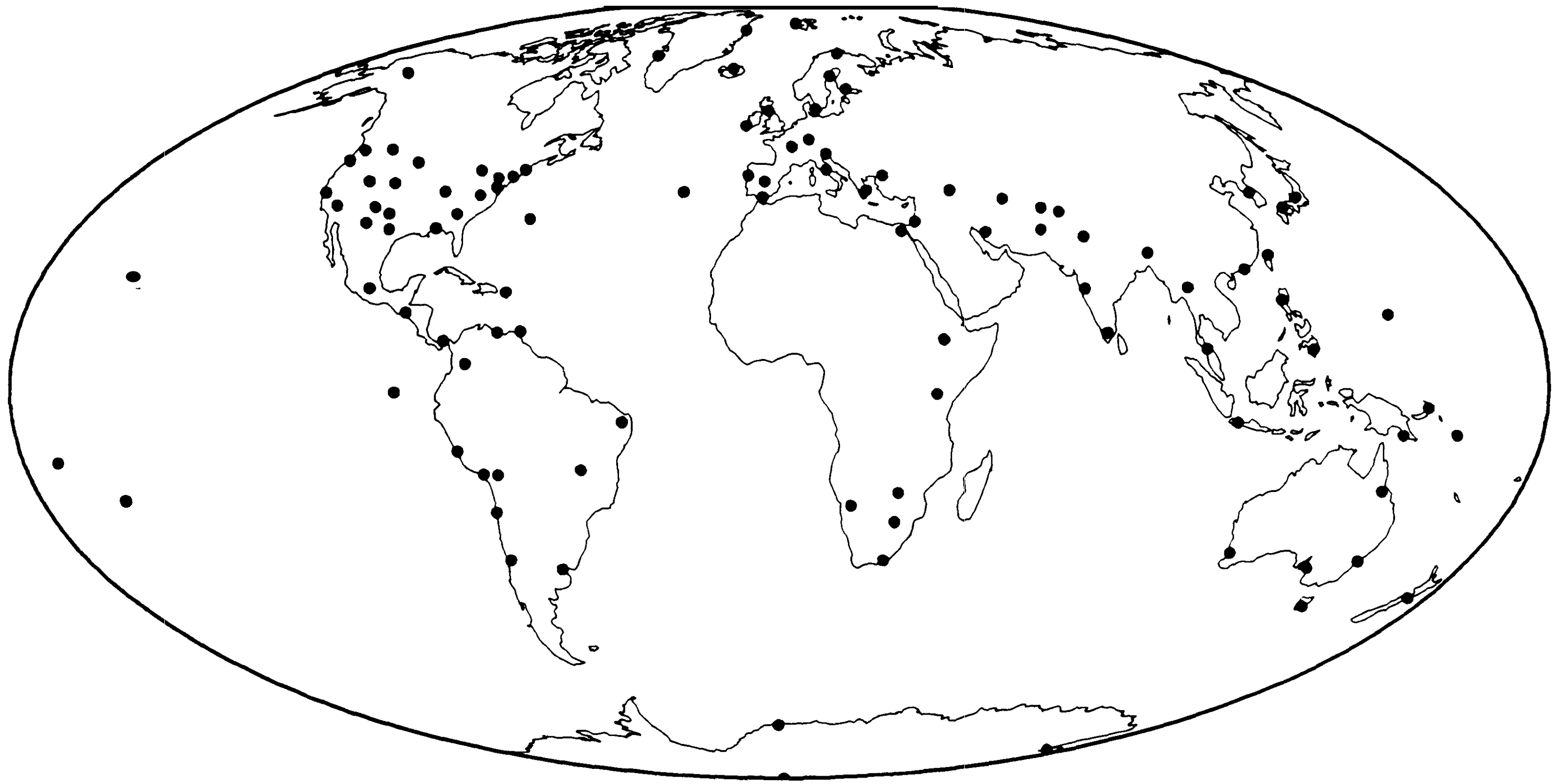
Figure 4-4.—Contributing Seismograph Stations (3,574 stations)



Seismic stations which routinely report data to the USGS National Earthquake Information Center (NEIC).

U.S. Geological Survey.

Figure 4-5.—Worldwide Standardized Seismograph Network (WSSN) Station Distribution



SOURCE: U.S. Geological Survey.

designed by the Department of Energy and now operated by the USGS. They were intended to be prototypes of in-country stations. There are five RSTN stations distributed over North America at inter-station distances that represent monitoring in the Soviet Union with 10 internal stations.

- The NORESS seismic array in Norway. This seismic array is funded by the Defense Advanced Research Projects Agency (DARPA) and the Department of Energy (DOE). The prototype array is located in southern Norway, an area thought to be geologically similar to the western part of the Soviet Union.
- The recently installed China Digital Seismic Network (CDSN), which is a cooperative program between the People's Republic of China and the USGS.
- The Atomic Energy Detection System (AEDS) seismic network. This network is operated by the Air Force Technical Applications Center (AFTAC). The purpose of the AEDS network is to monitor treaty compliance of the Soviet testing program. Consequently, the stations are located so as to provide coverage primarily of the U.S.S.R. The capabilities of the AEDS network are described in a classified annex to this report. The USGS and the AEDS stations are the main sources of routine information on Soviet testing.

In addition to these networks, there is also a jointly operated NRDC-Soviet Academy test site monitoring network in the United States and the Soviet Union. The network consists of three stations in each country around the Kazakh and Nevada test sites at distances of about zOO kilometers from the boundaries of each test site. These stations are supplying high-quality seismic signal data, in the high and intermediate frequency range from 0.1 Hz to about 80 Hz. The stations are designed to be modern prototypes of the in-country seismic stations required for monitoring a low threshold test ban treaty and they are not limited by system noise in the high frequency range. Plans call for the addition of five more such stations distributed across the Soviet Union and for several more to be similarly distributed across the United States.

Planned Networks

There are a number of planned new networks that will provide increased capability to detect, locate, and characterize seismic events around the world. These networks are being developed by the United States and other countries.

Hypothetical Networks

Existing unclassified networks external to the U.S.S.R. have an excellent capability for monitoring events with seismic magnitudes greater than 4.0 within the U.S.S.R. However, for explosions less than a few kt, the possibility exists that the seismic signals from such explosions could be reduced through an evasion method. To demonstrate a capability to defeat credible evasion scenarios that could be applied to explosions with yields less than a few kt, seismic stations within the Soviet Union would be necessary.

Obviously, there are a number of requirements for such internal stations and their data. Among these are the following: the data must be provided in an uninterrupted manner; the data must be of high quality; the seismic noise at the stations should be low; the operating parameters of the stations and the characteristics of the data should be completely known at all times; the data should be available to the United States within a reasonable time frame; the stations should be located for effective monitoring of the U. S. S. R.; and any interruption or tampering with the operation of the station should be detectable by the United States. Obviously, these requirements can most easily be achieved by deploying U.S. designed and built seismic stations within the U.S.S.R. at sites chosen by the United States.

The number of stations required within the U.S.S.R. is a function of a number of factors including: the threshold level down to which monitoring is desired, the seismic noise at the stations, the signal-to-noise enhancement capability of the stations, the signal propagation characteristics within the U. S. S. R., and the possibilities for various evasion scenarios thought to be effective within different areas of the U.S.S.R. Many seismologists have proposed distributions of internal stations capable of detecting seismic events down to various thresholds. The number of internal stations proposed for the various distributions ranges between 10 and 50.

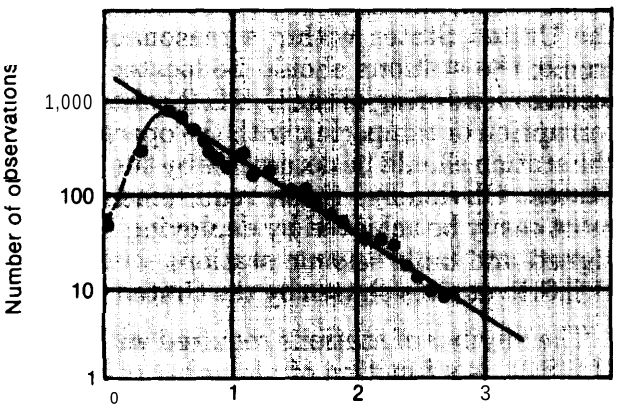
SEISMIC MONITORING CAPABILITY

Calculating Seismic Monitoring Capability

Calculating the detection capability of existing seismic stations is straightforward. For hypothetical stations, however, the detection capability must be estimated by adopting a number of assumptions. Because there exists a range of possible assumptions which can be argued to have validity, there are also a range of possible capabilities for a network of hypothetical internal stations.

For existing stations, the average detection capability is easily determined by observing the number of seismic events detected as a function of log amplitude (figure 4-6). The station can be expected to detect all events within a given region down to some magnitude level. A cumulative plot of the detections, such as illustrated in figure 4-6, will show that a straight line can fit these values down to this magnitude threshold level. This threshold marks the point where the station fails to detect all events. The 90-percent detection threshold (or any other threshold) can be determined from this plot. If the event magnitude rather than the observed amplitude is used, it is important that all magnitudes used in such plots be corrected for low-magnitude bias as previously discussed. By examining all stations of a network in this manner, the station detection parameters can be determined and used to compute overall network performance for the given region.

Figure 4-6.—Detection Capability of a Seismic Station



SOURCE: Modified from Air Force Technical Applications Center

For hypothetical internal stations, no detection statistics are generally available for computing the cumulative detection curve as a function of magnitude. Therefore, the detection capability must be estimated by assuming the following factors: the seismic noise at the station, the propagation and attenuation characteristics of the region through which the signals will travel, the efficiency of the seismic source, and the signal-to-noise ratio required for the signal to be detected. All the above factors must be evaluated in the frequency range assumed to be best for detecting a signal. The result of all these factors, when considered together, is to provide an estimate of the probability that a signal from a source of a given size and at a given location will be detected at a certain station. Individual station detection probabilities are then combined to determine the overall probability that four or more stations will detect the event. Translating this capability to situations where evasion might take place requires additional considerations (see ch. 6).

Global Detection Capability

There are many seismic stations that exist around the world from which data can be obtained. While no attempt has ever been made to determine the global detection capability of all these stations, a rough estimate could be made by reviewing the various reporting bulletins and lists. However, the current global detection capability does not really matter because it will soon change as various planned networks become installed. Consequently, an accurate assessment of global capability is best addressed by discussing planned networks.

For regions external to the U. S. S. R., and particularly for regions of the Southern Hemisphere, the greatest detection and location capability will reside not with the AEDS, but with a number of existing and planned seismic networks which are unclassified. This is a logical consequence of the AEDS being targeted primarily at events within the U.S.S.R. In particular, national networks such as those of Australia, China, the United States, Italy, and Canada will provide significant global capability.

Given all the national and global data sources, a cautious estimate of the global detection capability by the year 1991 (assuming 90 percent confidence of four or more stations detecting an event using only open unclassified stations) is m_b 4.2. For many regions, such as the Northern Hemisphere, the detection capability will be, of course, much better. Therefore, by 1991, any explosion with a magnitude corresponding to 1-2 kt well-coupled that is detonated anywhere on Earth will have a high probability of being detected and located by networks external to the U.S.S.R. Opportunities to evade the seismic network outside the Soviet Union are limited. Because evasion scenarios require large amounts of clandestine work, they are most feasible within the borders of a closed country such as the Soviet Union. Consequently, monitoring networks are designed to target principally the Soviet Union.

Detection Capability Within the U.S.S.R. Using No Internal Stations

Given that a large range of possible networks exists, a few type examples are useful to convey a sense of what can be accomplished. For example, the capability of a hypothetical network consisting of a dozen or so seismic arrays that are all *outside* the borders of the Soviet Union can be calculated. A cautious estimate is that if such a network were operated as a high-quality system, it would have 90 percent probability of detecting at four or more stations all seismic events within the Soviet Union with a magnitude at least as low as 3.5. This corresponds to an explosion having a yield below 1 kt unless the explosion is decoupled.

The hypothetical detection threshold of m_b 3.5 is considered cautious because it is known that a greater detection capability might exist at least for parts of the U.S.S.R. For example, the single large NORSAR array in Norway has the potential to achieve detection thresholds equivalent to an event of m_b 2.5 or lower (corresponding to a well-coupled explosion between 0.1 and 0.01 kt) overlarge regions of the Soviet Union.[1]

Also, fewer stations (fewer than the four needed above) may detect much smaller events, and this can provide useful information. However, detection by one or a few stations may not be adequate to, with high confidence, locate or identify events. Also, reductions of the detection threshold must be accompanied by a comparable capability to locate the events (for focusing other intelligence resources) and to separate nuclear explosions from earthquakes and legitimate industrial explosions.

Detection Capability Within the U.S.S.R. Using Internal Stations

Seismic stations located internalto a country for the purpose of monitoring have a number of important advantages: improved detection capability, improved location capability, and improved identification capability.

[1]The potential instantaneous detection thresholds for the large NORSAR array (42 seismometers spread over an area of about 3,000 km'), as described in "Teleseismic Detection at High Frequencies Using NORSAR Data" by F. Ringdal in *NORSAR Semiannual Technical Summary*, Apr. I-Sept. 30, 1984, are:

West of Ural Mountains-m_b	2.0-2.5 (possibly better)
Caspian Area–rob	2.0-2.5
Semipalatinsk—m_b	2.5-3.0
Siberia–m_b	2.5-3.5

Although much debate is associated with the predicted detection capabilities of internal stations, improved detection capability alone is probably not of the greatest significance at this time because the current detection capability is already very good. The improvement that internal stations will provide to *identification* capability (differentiating explosions from natural events) is by far the most important reason for requiring internal stations and should be considered the basic requirement for internal stations. The problem of detecting and identifying seismic events in the face of various evasion scenarios will be discussed in the next two chapters.

Based on cautious assumptions for a network of 30 internal arrays or about 50 three-component internal stations, it appears likely that a detection threshold of m_b 2.5 (90 percent probability of detection at four or more stations) could be reached. This corresponds to a well-coupled explosion of 0.1-0.01 kt, or a fully *decoupled* nuclear explosion with a yield of about 1 kt. Based on more optimistic assumptions about the conditions to be encountered and prospective improvements in data processing capability, this same network could have a detection capability as low as m_b 2.0. Detection capability contours for one such proposed 30-array internal network are shown in figure 4-7.

Considerations in Choosing Monitoring Thresholds

Depending on the number of internal stations, detection capabilities could either increase or decrease. The point, however, is that very low detection thresholds, down to magnitude 2.0, can be achieved. In fact, almost any desired signal detection level can theoretically be obtained by deploying a sufficient number of internal stations; although there maybe disagreements over the number and types of stations needed to achieve a given threshold. The disagreements could be resolved as part of a learning process if the internal network is built up in stages.

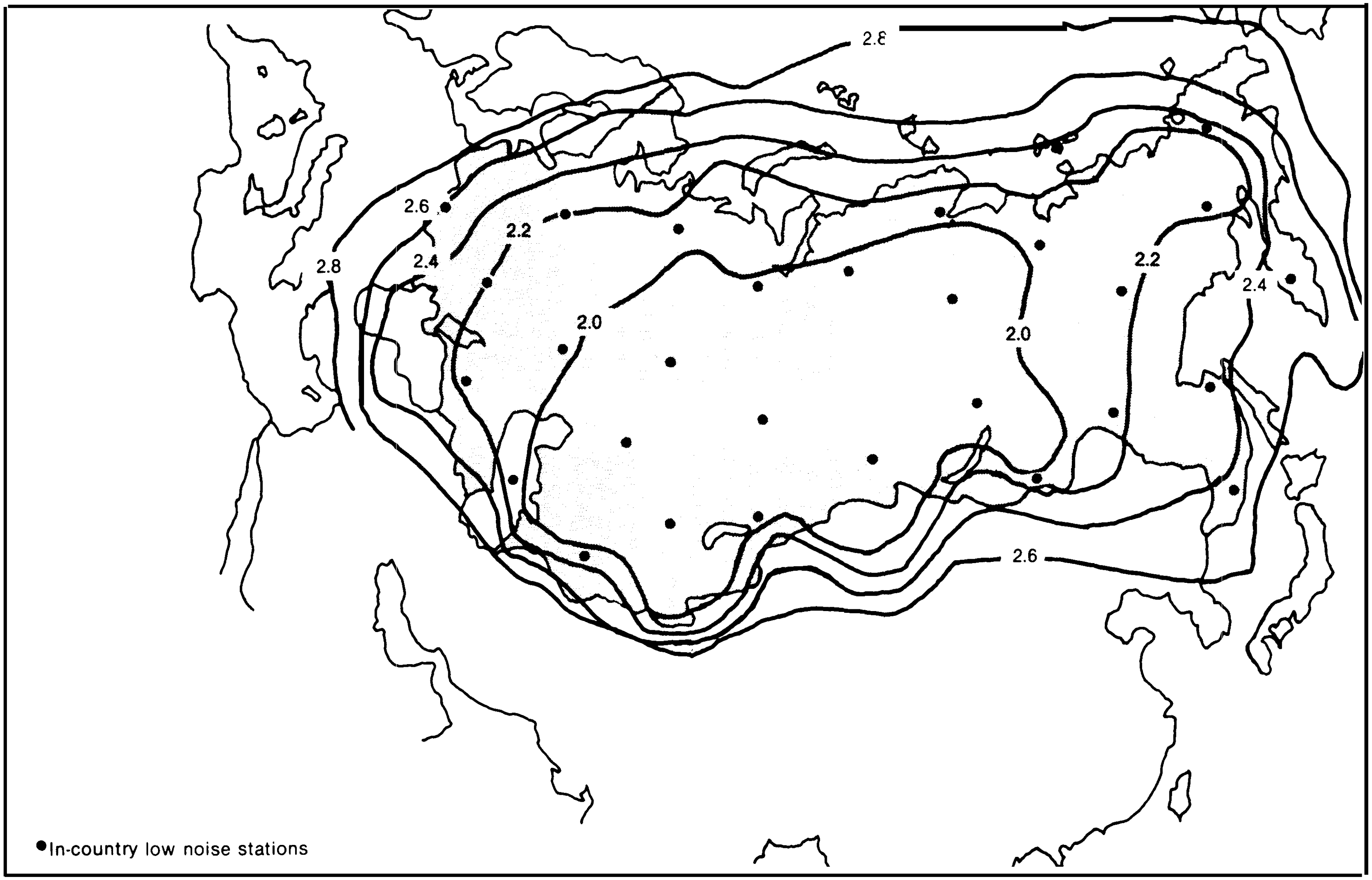
Another consideration is that all detection estimates used in this report are based on a 90-percent probability of four or more stations detecting an event. While this maybe a prudent estimation procedure from the monitoring point of view, an evader who did not wish to be caught might adopt a considerably more cautious point of view. (See chapter 2 for a discussion of the relationship between uncertainty and cheating opportunities.) Such concerns might be increased by the realization that for many seismic events, there will beat least one station that will receive the signal from the event with a large signal-to-noise ratio. The signal will be so large with respect to the noise at this station that the validity of the signal will be obvious and will cause a search for other associated signals from neighboring seismic stations. The possible occurrence of such a situation would be of concern to a country contemplating a clandestine test.

Throughout all of this discussion it must be kept in mind that an improvement in detection capability does not necessarily correspond directly to an improvement in our monitoring capability. Although a reduced detection threshold must be accompanied by a reduced identification threshold; occurrences such as industrial explosions might ultimately limit the identification threshold. For example, the estimate of detection capability for internal stations which is given above, m_b 2.0 to 2.5, corresponds to a decoupled explosion of about 1 kt. A decoupled 1 kt explosion produces the same m_b signal as a 1/70 kt (15) ton chemical explosion. At such small magnitude levels, there are hundreds of chemical explosions detonated in any given month in the U.S.S.R. and in the United States.

Use of High-Frequency Data

It has long been known to seismologists that seismic signals of moderate to high frequencies can indeed be detected at large distances from the source under favorable geological conditions. Such is the case in the eastern United States, and it is generally thought that this is also true of most of the Soviet Union. In con-

Figure 4-7.—Example of Calculated Detection Capability



Calculated detection capability (in m_b units) of an external network plus 30 internal, low-noise arrays.

SOURCE: Modified from Lawrence Livermore National Laboratory.

trast, tectonic regions such as the western United States and the southern fringe of the U.S.S.R. are generally characterized by stronger attenuation of high frequencies, which are therefore lost beyond relatively short distances.

The design and development of a nuclear monitoring strategy based on high-frequency seismic signals calls for:

- A determination of Earth structure within and around the region to be monitored, and an evaluation of its signal transmission characteristics at high frequencies.
- A methodology for identifying and selecting sites with low ground noise, and equipping such sites with high performance sensors and recording systems, so as to achieve the largest possible signal-to-noise ratio.
- A reliable understanding of the high-frequency radiation of natural (earthquakes) and man-made (explosions) seismic sources. Although empirical evidence based on direct observations is sufficient in principle, a predictive capability, based on theory, is required to assess properly new and untested monitoring conditions.

Such requirements parallel in every respect the usual constraints placed on standard monitoring systems. However, direct experimentation pertinent to high-frequency monitoring has been rather limited so far, and the relevant data available today are neither abundant nor diverse. Consequently, an assessment of whether these requirements can be met relies of necessity on some degree of extrapolation from our present experience, based on theoretical arguments and models. This situation leaves room for debate and even controversy.[2]

Recently, it has been argued that the capability to detect and identify low-yield nuclear explosions could be greatly improved by using high-frequency (30 -40 Hz) seismic data.[3] The major points of the argument are:

- that natural seismic ground noise levels are very low at high frequencies, and that large seasonal fluctuations are not anticipated;
- that careful station selection could make it possible to emplace seismic sensors in particularly quiet sites; and
- that present seismic recording technology allows high-fidelity recording; by suppression of system-generated noise to levels below ground noise even at high frequencies and at quiet sites.

Advocates of high-frequency monitoring explain the efficiency of high-frequency wave propagation observed in the North American shield in terms of a simple model for attenuation of seismic waves in stable continental regions and argue that the model applies as well to stable continental Eurasia. Finally, they argue that suitable parameterizations of theoretical models of earthquakes and underground explosions provide adequate predictive estimates of the relative production of high-frequency energy by various seismic sources and justify their choice by comparison with limited observations.

Based on these arguments and a systematic modeling procedure, some seismologists reason that the most favorable signal-to-noise ratio for detection of low yield (i.e. small magnitude) events in stable continental areas will be found at moderate to high frequencies (about 30 Hz). They further infer that a well-designed network of 25 internal and 15 external high-quality stations using high frequencies would yield multi-station, high signal-to-noise detection of fully decoupled 1-kt explosions from any of the potential decoupling sites within the U. S. S. R., and result in a monitoring capability at the l-kt level.

On the other hand, the inference that such significant benefits would necessarily accrue

[2] High quality seismic data is now becoming available from the NRDC-Soviet Academy of Sciences stations in the Soviet Union and the United States, with more widely distributed stations to be added in 1988 in both countries. This data may help reduce the necessity for extrapolation and decrease the uncertainties that foster the debate.

[3] For example, J. F. Evernden, C. B. Archambeau, and E. Cranswick, "An Evaluation of seismic Decoupling and Underground Nuclear Test Monitoring Using High-Frequency Seismic Data," Reviews *of Geophysics,* vol. 24, No. 2, 1986, pp. 143-215.

by relying on high-frequency recordings has been strongly questioned in the seismological community. Indeed many scientists feel that the case is currently unproven. Major points of disagreement include:

- The concern that the theoretical seismic source models used so far in the analysis described above are too simple. Studies aimed at constructing more realistic models indicate that the high-frequency waves generated by seismic sources are strongly affected by complexities of source behavior that the simple models do not take into account. On the other hand, advocates of high frequency seismic monitoring believe that the models they have used have successfully predicted a number of characteristics of seismic sources that were subsequently verified and that none of the many well-documented observations of seismic wave characteristics from large events are in conflict with their theoretical model predictions. Thus they argue that the model predictions, for somewhat smaller events at somewhat higher frequencies than are ordinarily studied, are reasonable extrapolations.
- The concern that it may be difficult to identify candidate station sites where the high-frequency noise is sufficiently low to permit actual realization of the desired benefits. Experience to date is limited, and one does not really know whether a given site is suitable until it has been occupied and studied for at least a year. On the other hand, advocates of high frequency monitoring feel that suitable low-noise sites are not at all rare and can be rather easily found in most, if not all, geologic environments within the continents. They argue that stations selected so far have had adequately low high-frequency noise characteristics and the selection process was neither difficult nor time consuming. They conjecture that doubts are based on misidentification of high-frequency internal seismic recording system noise as ground noise, and that once high-performance systems with low system noise become more wide-spread, this concern will disappear.
- The concern that observations which can be employed to test directly the validity of the proposed use of high frequencies are as yet quite scant, and their interpretation is not free of ambiguities. For example, the characterization of source spectra and the propagation and attenuation of high-frequency waves remain issues which are not resolved unequivocally by observations, and yet are critical to the formulation of a high-frequency monitoring strategy. Similarly, available data often exhibit an optimal signal-to-noise ratio at frequencies near 10 Hz, in apparent disagreement with the arguments enunciated earlier. In response to these concerns, proponents argue that the NRDC-Soviet observations of signal-to-noise ratios greater than 1 and out to frequencies above 20 Hz provides evidence for the potential of high frequency monitoring. While proponents of high frequency monitoring agree that the observations of the largest signal to noise ratios for signals from seismic events often occur near 10 Hz, this is not in disagreement with the predictions or technical arguments advanced for high-frequency monitoring. They argue that these observations are obtained from seismic receivers with system noise that is greater than ground noise at frequencies above 10 Hz, and that many of the observations are from industrial explosions that are ripple-fired and so are expected to have lower high-frequency content than a small nuclear test.
- The concern stated earlier that the motivation for the proposed high-frequency monitoring approach uses contested theoretical arguments and models to extrapolate from our present experience and thus attempt to guide further steps towards a significantly improved capability. In the present case, models are used to extrapolate both toward high frequencies and toward small yields, and just how far one

may extrapolate safely remains a matter of debate. The proponents of high frequency monitoring agree that the data relating to high frequency monitoring is limited with respect to the geologic regions to which it pertains. Furthermore, it is clear that experience in the systematic detection and identification of very small seismic events using high-frequency data is absent and that, as a consequence, it has been necessary to extrapolate from experience with larger seismic events where lower frequency data is used. Proponents believe, however, that what limited data is available does support the most critically important predictions; these being the apparent availability of low-noise sites and the efficiency of high-frequency wave propagation to large distances.

These controversial aspects notwithstanding, there is general agreement among seismologists that good signal-to-noise ratios persist to higher frequencies than those used routinely today for nuclear monitoring. In particular, data in the 10-20 Hz band show clear signals which are undoubtedly not used optimally. Given the fact that recording of even higher frequencies is demonstrably feasible in some situations, and given the potential advantages for low-yield monitoring, the augmentation of our experience with such data, the concomitant continued development of appropriate analysis techniques to deal with them, and the validation of the models used in their interpretation are goals to be pursued aggressively. Not until a sufficient body of well-documented observations of this nature has been collected can we expect to achieve a broad consensus about the performance of high-frequency monitoring systems.

Arrays v. Three-Component Stations

Both small-aperture, vertical-component arrays such as NORESS, and three-component, single-site stations such as the RSTN station have been considered for use as internal stations. In choosing which to use, it should be realized that many combinations of arrays and single stations will provide the same capability. For example, for any array network, there is a single station network with comparable capability; but the network of single stations probably requires about twice as many sites. Although a single array has advantages over a single three-component station (see chapter 3), for monitoring purposes it is preferable to have a large number of station sites with three-component stations rather than to have a small number of sites with arrays. This is true because it permits better accommodation to details of regional geology, and better protection against noise sources temporarily reducing capability of the network as a whole. However, if the number of sites is limited by negotiated agreement, but the instrumentation can include either arrays or three-component stations, then arrays are preferable. This is true both because of the inherent redundancy of arrays and their somewhat better signal-to-noise enhancement capability over single three-component stations.