2

CTBT Monitoring Capability

The energy released by a nuclear test explosion generates signals that are potentially detectable by radionuclide sensors, by optical and other electromagnetic sensors (both ground-based and satellite-based), and by elastic wave sensors (infrasound, hydroacoustics, seismology).

From the point of view of a CTBT State Party considering clandestine evasion, all of these signals must be kept low enough to prevent detection and identification—or at least to inhibit attribution. Numerous signals are recorded on a daily basis from non-nuclear sources and numerous data streams need analysis from each sensing technology to explore the evidence of a possible nuclear test. The monitoring institutions need to develop confidence in the ability to detect, identify, and attribute.

An analysis of overall monitoring capability requires consideration of all available technologies, often in combination. What counts is the capability of the whole monitoring system. But inevitably, a detailed evaluation has to explore the separate techniques. Table 2-1 summarizes the way in which several different technologies contribute to monitoring four different environments (underground, underwater, atmosphere, and space). The first four technologies listed in Table 2-1 are used by the International Monitoring System (IMS) of the Comprehensive Test Ban Treaty Organization (CTBTO), headquartered in Vienna, Austria. The fifth technology (electromagnetic) uses sensors of many types, none of which are used by the IMS. They can include ground-based or space-based detectors of the characteristic flash of a nuclear explosion in the atmosphere or in space. Information on nuclear testing in any environment potentially can also be provided by signals intelligence. The sixth technology, satellite photography, now available commercially at 1-meter resolution (limited by U.S. government policy and not technology), can be used for remote examination of activity at and effects on sites on land and in the ocean.

Table 2-1 Contributions of key technologies to CTBT monitoring of different test environments

Monitoring Technologies	Underground	Underwater	Atmosphere	Near Space
Seismic	major	major	secondary	none
Radionuclide	major	major	major	none
Hydroacoustic	secondary	major	secondary	none
Infrasound	secondary	secondary	major	none
Electromagnetic	secondary	secondary	major	major
Satellite Imagery	major	major	secondary	secondary

Although there are synergies among these different CTBT monitoring technologies and all of them are needed, seismology is the most effective for monitoring against the underground testing environment, which is the one most suited to attempts at clandestine treaty evasion. From the viewpoint of a sophisticated evader, this environment is also the one most suited to evaluating the performance of nuclear-weapon components via explosive testing. We therefore give emphasis to seismic monitoring of the underground environment.

Starting in the late 1940s, the United States developed a capability to monitor atmospheric nuclear tests and was successful in detecting the first, unsuspected Soviet nuclear test in late August 1949 by routine air sampling over the Pacific Ocean. Over the next decade the system for air debris sampling and infrasound detection was developed and an initial network of seismic stations was established to monitor anticipated underground testing. The Limited Test Ban Treaty (LTBT) of 1963 (banning signatories from nuclear testing underwater, in the atmosphere, and in space) did not incorporate an independent international monitoring system, but depended on the Nuclear-Weapon States' independent national technical means (NTM), which were directed at keeping track of each other's nuclear programs and possible testing by Non-Nuclear-Weapon States. The international community at the time appeared satisfied that this system of NTM monitoring was adequate.

For the next decade the United States (and presumably the Soviet Union) improved its worldwide monitoring system with substantially improved seismic capabilities and a variety of satellite sensors to monitor atmospheric and space nuclear explosions. In 1974, the United States and the Soviet Union signed a bilateral Threshold Test Ban Treaty, banning underground nuclear tests of yield greater than 150 kt,[1] which involved extensive, close cooperation between the two states, and led to mutual understanding of the relationship between seismic magnitude[2] and yield of tamped underground nuclear explosions at their respective test sites[3]—a subject in longstanding dispute.[4] As an example of informal cooperation, in 1977 the Soviet Union called the attention of the United States to apparent South African preparations for an underground test in the Kalahari desert that had been missed by U.S. intelligence and that led to actions that prevented further activity at the site.

With international efforts to negotiate a comprehensive test ban in the mid-1990s, the international community was no longer satisfied to rely on the NTM capabilities of the Nuclear-Weapon States (primarily the United States) to monitor the treaty, but wanted it to be based on a truly internationally-operated system with information available to all parties. While the new system in many ways duplicates existing NTM capabilities, it adds significantly to those capabilities and makes the CTBT a genuinely international undertaking. This makes possible the establishment of a much denser network of monitoring stations and the international acceptance of challenge inspections. The treaty is designed so that both the international system and NTM can be used to carry out the monitoring function.

A significant difference between international monitoring efforts and monitoring by NTM is that the former must treat the whole world more or less equally, while the latter can concentrate on particular nations that are of concern to the United States. NTM can also focus on

[1] A kiloton is the energy unit usually used for specifying the energy released in a large explosion. Originally it was taken to be the energy released by a thousand tons of TNT, but a kiloton is now defined as a trillion calories (4.2×10^{12} joules).

[2] This is the Richter magnitude, based on the logarithm of the amplitude of seismic waves recorded at large distances. Different types of seismic waves are described in the following section. As a logarithmic scale, an increase in magnitude by one full unit implies an increase by a factor of ten in the amplitude of ground motion. An increase in seismic magnitude by 0.3 units corresponds to a factor of two in amplitude.

[3] A tamped explosion is one in which there is little or no space between the explosive device and the surrounding rock; and the device is detonated at sufficient depth so that all the gas and other by-products of the explosion are largely, if not completely, contained beneath the ground surface.

[4] This experience is useful in translating the capability to monitor the CTBT, expressed in terms of seismic magnitude, into the capability to monitor expressed in terms of the equivalent yield of a tamped underground nuclear test. Documentation from Russia, made available in recent years, provides added validation of this monitoring experience.

particular regions within the countries of concern. Monitoring nuclear testing by NTM has been a reality for more than 50 years, often with efforts that were concentrated on active nuclear test sites. It can be expected to be exceedingly difficult if not impossible for monitoring stations, operated on behalf of agencies with responsibility for U.S. NTM, to be installed in certain parts of the world of concern to the United States. But in many cases the international system can make installations in such regions. (It would be a setback to U.S. monitoring efforts if it were denied access to data from the International Monitoring System as a result of a U.S. failure to fulfill its financial obligations to the IMS or for other reasons.) We assume that investments in monitoring systems will continue to be made if evasion is regarded as feasible and of significant impact. In this connection, it is important that airborne radionuclide detection capabilities and specific satellite payloads be considered for their contribution to national security and not simply, as has sometimes happened, as a cost to an agency's budget.

In the sections that follow, we describe general aspects of all monitoring technologies, review current capabilities for monitoring the four different testing environments, describe what can be done with confidence-building measures and on-site inspections, and give our conclusions on monitoring capabilities overall.

General Aspects of All CTBT Monitoring Technologies

The CTBT will in practice be monitored by:

- the international CTBT Organization in Vienna, Austria;
- National Technical Means, which for the United States includes the Atomic Energy Detection System (AEDS) operated by the Air Force Technical Applications Center (AFTAC); and
- the loosely organized efforts of numerous institutions, acquiring and processing data originally recorded for purposes other than treaty monitoring, e.g. from regional and national networks of seismic and radionuclide sensors. Hundreds of institutions continuously operate thousands of seismometers; and seismically active regions of North America, Europe, Asia, North and South Africa, and the Middle East are now routinely monitored down to low magnitudes in order to evaluate earthquake hazards.

The international monitoring effort based in Vienna is specified partly by the CTBT text and partly by parallel agreements signed by countries specifying their commitments to the CTBT Organization. The CTBTO operates an International Data Centre (IDC) using data contributed by the radionuclide, seismic, infrasound, and hydroacoustic networks of the International Monitoring System. Figure 2-1 shows the location of more than 300 stations of the IMS, using different symbols for the 50-station primary seismic network, the 120-station auxiliary seismic network, and the 60-, 80-, and 11-station networks for infrasound, radionuclide, and hydroacoustic technologies, respectively. All these stations are to have a satellite link to the IDC in Vienna, some sending data continuously (e.g., the primary seismic network), others sending data only on request or at regular intervals.

Monitoring for underground nuclear explosions usually entails:

(a) detecting signals recorded by each sensor of a particular network;
(b) associating into a single group the various signals (from different sensors) that appear to be generated from a common source, often called an "event";
(c) estimating the location and time of that event and the uncertainty of the location estimate;

(d) identifying the nature of the event—whether suspicious or not in the context of CTBT monitoring; and
(e) attributing the event, if it is a nuclear explosion, to a particular nation.

The role of the IDC in event identification, is that of “Assisting individual States Parties ... with expert technical advice ... in order to help the State Party concerned to identify the source of specific events."[5] The responsibility of identification and attribution is left to each State Party. The IDC assists by carrying out a process called event screening, described below. The treaty mandates that each State Party maintain a National Authority to serve as the national focal point for liaison with the CTBTO and with other signatories. The U.S. National Authority for the CTBT would be a new entity.[6]

Much of the work of CTBT monitoring is routine, for example estimating the location of 50 to 100 earthquakes per day. In contrast, several years of experience with predecessors to the current IDC have shown about once or twice a year that some particular events have needed special attention to interpret their nature, including special efforts to acquire data from stations not operated by the IMS that recorded the event of interest. Examples include two mine collapses in 1995 (one in the Urals, the other in Wyoming); a small earthquake on August 16, 1997 under the Kara Sea near Russia's former nuclear test site on Novaya Zemlya; and two underwater explosions in August 2000 associated with loss of a Russian submarine in the Barents Sea.

Assessments of monitoring capability are typically made by evaluating routine procedures for detection and identification, since these are the methods that are first applied to an event of interest. It is necessary to make a prompt evaluation so that additional resources can be brought to bear on events deemed suspicious. The location and identification of events subjected to special study are more reliable, since they are based on more data and on methods of analysis that can be more complete and more sophisticated.

In this report we assess monitoring capabilities in two ways: first, against nuclear tests conducted in the manner typical of past practice by the Nuclear-Weapon States, with no effort to conceal signals; and second, against various evasion scenarios intended to reduce and/or mask the signals of a nuclear test, and thus to prevent detection, identification, and attribution.

There is a considerable degree of consensus among experts on the capability of various networks to monitor the first type of nuclear testing. This capability is significantly better than has commonly been believed. For monitoring against evasion scenarios, the issues are whether the proposed scenario is practical in view of the number of different ways that tests are monitored, and whether the scenario has utility for weapons development.

Concerning the step of attributing an identified nuclear test to a particular nation, procedures would differ somewhat depending on the environment in which the test was conducted. For the underground environment, there is the potential for long-lasting indications of the testing location (for example, a shaft or tunnel leading to a chamber with radioactive indicators of the explosion), whose coordinates may be estimated from seismic data followed up by identification of the site from satellite photos and other data, perhaps acquired as part of an on-site inspection. Attribution is likely to be more problematic for an underwater or atmospheric test, since a nation with a nuclear explosive could detonate it on a ship or a plane and the effects on the surrounding media would be more ephemeral. Though such a test would likely be detected and located, it might be attributed only with difficulty to the nation responsible. Measurement of the yield and other aspects of the explosion could be done to some extent through radiochemical analysis of

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[5] U.S. Department of State, “Protocol to the Comprehensive Nuclear Test Ban Treaty” 24 September 1996, pt. I, para. 20(c), http://www.state.gov/www/global/arms/treaties/ctb.html.

[6] Details of how this entity would operate have yet to be determined. The U.S. National Authority for the Chemical Weapons Convention is organized within the Department of State, and a similar arrangement is contemplated for the CTBT, with input from other agencies.

one or more debris samples, and from the strength of seismic, hydroacoustic, and/or infrasound signals. Radionuclide collection may lead to identification of the type of nuclear explosive, in turn associated with the type of design used by a particular nation. To confidently evade attribution, a tester would need to believe that the United States, working with other nations, did not have the capability to track ships and planes in the vicinity of the test location, and would not intercept communications relating to the test. Attribution of a nuclear test in space is less of a problem, because of intensive efforts now made to track all objects launched into this environment.

Finally on this subject, we note that discussion of attribution is complicated when considering the possibility of a country that designs a nuclear explosive device and tests it on the territory of another country. The physical evidence of the test would point to the second country, which (if it provided assistance and was a State Party) would be a CTBT violation by the second country. Identification of the first country would most likely have to be made by NTM, including intelligence methods, or with the assistance of the second country.

Monitoring Underground Nuclear Explosions

Underground nuclear tests are primarily monitored with seismic and radionuclide signals. Important information can also be provided by satellite imagery.

Seismic signals are traditionally grouped into teleseismic waves and regional waves, depending on the distance at which they are observed. Teleseismic waves propagate either as “body waves” through the Earth's deep interior, emerging with periods typically in the range 0.3 to 5 seconds at distances greater than about 1,500 km, or as “surface waves” (analogous to the ripples on the surface of a pond) with periods of about 20 seconds. Because teleseismic waves do not greatly diminish with distance in the range from about 2,000 to 9,000 km, they are suited to monitoring a large country from stations deployed outside that country's borders. Teleseismic body waves are further subdivided into P-waves and S-waves. P-waves, which are the fastest-traveling seismic waves and are therefore the first to arrive, are particularly efficiently excited by explosions. Earthquakes tend to excite S-waves more efficiently. Teleseismic waves were the basis of most U.S. monitoring of foreign nuclear tests prior to 1987. Regional waves are of several types (including P-waves and S-waves), all propagating only at shallow depths (less than 100 km) with periods as short as 0.05 seconds, and they are regional in the sense that typically they do not propagate to teleseismic distances.[7] The word regional here carries the additional implication that such waves are dependent on local properties of the Earth’s crust and uppermost mantle—which can vary strongly from one region to another. Regional wave amplitudes recorded up to about 1,200 km from a shallow source are typically larger than teleseismic wave amplitudes recorded at distances greater than 1,800 km, but regional waves are complex and harder to interpret than teleseismic waves. For sub-kiloton explosions, teleseismic signals can be too weak for detection at single stations and monitoring then requires regional signals.

The utility of regional waves is demonstrated by experience with monitoring the 340 underground nuclear tests now known to have been conducted at the Semipalatinsk test site of the Soviet Union in East Kazakhstan during the period 1961–1989. These explosions were mostly documented at the time by Western seismologists using teleseismic signals. But when archives of regional signals from Central Asia became openly available following the break-up of the Soviet Union, it became possible to detect and locate 26 additional nuclear explosions at this test site, most of them sub-kiloton, that had not been recognized or documented with teleseismic sig

[7] An exception is the Lg wave, consisting of shear wave energy trapped in the Earth's crust, and which under favorable circumstances can propagate to distances of several thousand kilometers.

nals.

All modern seismographic stations operated to high standards (including all IMS stations) use broadband sensors, with high dynamic range and digital recording of motions in three directions (up/down, North/South, East/West).[8] At many IMS stations, arrays of vertical component sensors are also operated. A seismographic array consists typically of between 5 and 30 sensors with short-period response, spaced over several square kilometers, and operated with a central recording system. Arrays provide the ability to detect smaller signals by taking advantage of the known correlation structure of signals and noises, and the ability to estimate the directions from which signals are arriving at the station by interpreting the time sequence at which signals reach individual sensors. The CTBT Protocol lists 50 primary station sites around the world (see Figure 2-1) at which either a three-component seismographic station or an array of seismometers is operated, sending continuous data in near-real time by satellite to the International Data Centre.[9] Much experience is now available from a network of similar size, operated since January 1, 1995, initially under the auspices of the Geneva-based Conference on Disarmament which negotiated the text of the CTBT, and later with endorsement from the CTBTO in Vienna. The associated data center, based near Washington, DC, became the Prototype IDC (PIDC) shortly after the CTBT was opened for signature in 1996, and served for 5 years as the test bed for many procedures that were taken up by the Vienna-based IDC in February 2000.

Data from the 50-station primary network provide the basis for event detection by the IDC and for initial estimates of source location. For events whose location and other attributes are likely to be better quantified by additional signals, the CTBT Protocol lists an additional 120 sites around the world at which either a three-component seismographic station or an array is to be operated. These stations, which constitute the IMS auxiliary network with locations also shown in Figure 2-1, record continuously; but their data are sent to the IDC only for time segments requested by a message from the IDC. Much experience with such an auxiliary network has been acquired by the Prototype IDC. During the 5-year time period from January 1995 to February 2000, the PIDC made available (at http://www.pidc.org) a number of reports of global seismicity derived from the primary and auxiliary networks. The most important report is the daily Reviewed Event Bulletin, typically published 3 to 5 days in arrears, listing the events that have occurred that day, including location estimates and their uncertainties, magnitudes, a list of the reporting stations for each event, and arrival times of detected seismic waves at these stations. About 50 events have been reported each day on average, with some wide variations, for a total of about 100,000 events in the first 5 years. The production of reviewed bulletins must be done combining all four monitoring technologies used by the IMS (seismology, hydroacoustics, infrasound, and radionuclide monitoring). In practice, normally all of the events reported each day by the IDC are either earthquakes or mining blasts. Nuclear explosions by France and China prior to their signing the CTBT in September 1996 were widely recorded and promptly characterized, as were nuclear explosions of India and Pakistan in May 1998.[10]

The transfer of IDC operations to Vienna in February 2000 has been associated with a significant change in practice, namely that the daily Reviewed Event Bulletin is no longer being

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[8] A “broadband” sensor can record teleseismic surface waves and body waves, as well as the much higher frequencies of regional waves.

[9] These data, as for all IMS data sent to the IDC, include information authenticating that the sensor and its data stream have not been compromised.

[10] In 1998, more than 60 IMS stations detected the Indian test of May 11 and the Pakistani test of May 28, while more than 50 detected the second, smaller Pakistani test of May 30. The Indian government announced that it also conducted two subkiloton tests on May 13 at 06:51 Greenwich Mean Time. No such tests were detected at the regional stations that had acquired large signals from the Indian test two days earlier. Because the May 11 explosion was detected at many stations, with signal/noise that in one case exceeded 1,000, it is clear that the existing seismic network was capable of detecting a very small Indian test if the test actually occurred. The seismic signals from any Indian test on the May 13 event were at least 500 times smaller than those of the May 11 event. There is no indication that evasion attempts played a role in concealing the later announced test. See B. Barker, et al., “Monitoring Nuclear Tests,” *Science* 281 (1998): 1968-1969.

made openly available to the research community. The IDC makes this bulletin (and all IMS data upon which it is based) available to National Data Centers, but restricts further dissemination. The quality of IDC operations would be greatly enhanced in the long term by having a diverse community of data users. Many States Party, including the United States, have indicated their position that all IMS data should be made openly available without delay.

Seismic Detection Capability

Based on experience with noise measurements and station operations, the expected detection threshold of the CTBT primary seismographic network when completed is shown in Figure 2-2 in terms of contours of seismic magnitude. From events at this threshold and above, entailing detection of the first-arriving signal (always a P-wave) at three or more stations, a useful location estimate can be made. The auxiliary network does not contribute to the IMS detection capability shown in Figure 2-2, because as currently planned, data from this network are not available to the IDC unless requested for specific time segments—for example to enhance the data set collected from an already-detected event.

To interpret detection threshold maps such as shown in Figure 2-2 in terms of underground explosive yield we must use magnitude-yield relationships, which for tamped underground explosions typical of past experience are known to show some variability for different source regions, different depths for the explosion, and different propagation-path geologies. Table 2-2 lists yields as a function of decreasing magnitude for two representative magnitude-yield relationships in hard rock. The first (Y_1) is based on a relationship derived from extensive studies of Soviet underground nuclear testing at Semipalatinsk, Kazakhstan.[11] The second (Y_2) uses a relationship which is more appropriate for small explosions fired at a fixed depth.[12] Table 2-2 also indicates approximate yield values that are representative of hard rock explosions with magnitude 3.5 and smaller. Figure 2-3 uses these approximate yield values to indicate yield detection thresholds of the IMS primary seismic network for major parts of Europe, Asia, and Africa. Thus Figure 2-3 is an expanded view of part of the global map in Figure 2-2, but with magnitude contours now interpreted as approximate yields (via Table 2-2) for small tamped explosions in hard rock.

Table 2-2 Yields (in kilotons) of small nuclear explosions tamped in hard rock that correspond under different assumptions to a set of decreasing seismic magnitudes. (The approximate values listed in the final column are used in Figure 2-3 to indicate detection thresholds in terms of nuclear yield for tamped explosions in hard rock.)

Seismic Magnitude	Y1	Y2	Approximate Y
3.50	0.055	0.125	~0.10
3.25	0.025	0.071	~0.06
3.00	0.012	0.040	~0.03
2.75	0.005	0.022	~0.02
2.50	0.003	0.013	~0.01

[11] Magnitude = 4.45 + 0.75 log Y (in kt): see for example F.Ringdal, et al., "Seismic Yield Determination of Soviet Underground Nuclear Explosions at the Shagan River Test Site," *Geophysical Journal International* 109 (1992): 65-77. The slope here, with value 0.75, is less than unity because larger shots are usually fired at greater depth, and hence couple less efficiently into seismic energy. This manitude yield relation applies to the southern Novaya Zemlya test location and (with slightly lower intercept of about 4.25) to the northern Novaya Zemlya test location.

[12] Magnitude = 4.4 + log Y (in kt).

Yields at a given seismic magnitude can be different from those listed in Table 2-2 to the extent that an explosion is not tamped and/or not in hard rock. Thus, explosions in clay or water couple more efficiently into seismic signals so that the yield producing a given magnitude can be 10 or more times smaller than listed. Explosions in soft rock couple less efficiently and the yield producing a given magnitude can be 10 or more times larger than listed. An explosion in an underground cavity also couples less efficiently, raising the question of evasive testing, discussed below.

Figure 2-3 is important as indicating that the detection capability of the IMS primary seismic network is very significantly better than 1 kt for nuclear explosions conducted in a fashion typical of past underground nuclear testing (i.e., tamped and without efforts to reduce signals). For most of Europe, Asia, and Northern Africa, the detection threshold is down in the range from 30 to 60 tons in hard rock. The IMS was intended (but not formally specified) to support monitoring down to about one kiloton. During most of the more than 20 years of planning and building up the seismic components of this network, monitoring experience was almost all based on teleseismic waves although it was expected that regional waves would be superior for monitoring at lower yields. The IMS was designed with station spacing sufficiently close to enable use of regional waves, but it is only now becoming apparent from results such as those of Figures 2-2 and 2-3 that regional waves enable monitoring to be done well below 1 kt.

Association of Signals

A consequence of the low thresholds indicated in Figures 2-2 and 2-3 is the large number of seismic events that are detected and therefore require some analysis. Each year, somewhat more than 7,000 earthquakes occur worldwide with magnitude greater than or equal to 4, and about 60,000 with magnitude greater than or equal to 3. While chemical explosions having magnitude greater than or equal to 4 are rare (a few per year, if any), there are probably on the order of a few hundred per year worldwide with magnitude greater than or equal to 3, and many thousands per year at smaller magnitudes that are detectable with stations close enough.

The problem then arises of sorting through the tens of thousands of signals each day that will be detected from network analysis of array data and three-component station data, and collecting together all the signals that are associated with the same seismic source.[13] In the work of assembling sets of detections common to the same event, array stations in principle have the advantage, over three-component stations, of permitting determination of the direction of the source from a station at which there is a detection.

Associating signals correctly to the underlying seismic events is currently the most challenging software problem at the IDC. This challenge has been met in recent years for detections from the primary network. It could also be met using a larger network (for instance, with the addition of the auxiliary network, if it were enabled to report continuously), which would drive detection thresholds down to lower magnitude.

[13] Each seismic source generates several different waves, each arriving at a different time. Signals from different events can therefore overlap in time at each station. Effective methods of sorting through the interspersed detections have been found, but in practice 40 percent or more of the detections recorded on a given day have remained unassociated at the PIDC. The unassociated signals are typically from events of such small size that they are not detected by three or more stations, and have magnitudes lower than those contoured in Figure 2-2. These unassociated detections from low magnitude events are an unavoidable consequence of operating a very sensitive network.

Location of Seismic Sources

In practice, location estimates are needed for all the events for which a set of detections can be associated, since an interpretation of the location (including the event depth) is commonly used to reach preliminary conclusions on whether an event could possibly be an explosion. It can be crucial to know if an event is beneath the ocean, or possibly on land; if it is more than 10 km deep, or possibly near the surface; if it is in one country, or another. The source-station distance and azimuth can be roughly estimated from data at a single station, such estimates being much better in the case of an array station than for a three-component station. The accuracy of a location estimate is best characterized with a confidence interval, and typically detections at three or more stations are needed for confidence intervals to be calculated.

The CTBT Protocol, Part II, paragraph 3, states that "The area of an on-site inspection shall be continuous and its size shall not exceed 1,000 square kilometers. There shall be no linear dimension greater than 50 kilometers in any direction."

This condition presents a challenge for those who may have to estimate the location of an event that could become the basis of an on-site inspection request. The challenge is especially difficult for small events, when the estimate may have to be based upon regional seismic waves alone. Regional waves can be used to make accurate location estimates, but only in regions that have previously been well studied.

The treaty language limiting the area of an on-site inspection has been taken by the monitoring community as setting the goal of locating seismic events with 90 percent confidence intervals no greater than 1,000 square km in area. This goal is being actively pursued. Methods first developed and applied to seismic events in Northwestern Europe and North America entail calibration of IMS stations in these regions, by developing station-specific information on the travel-times of regional waves arriving from sources at different distances and azimuths. These methods are now being extended to IMS stations in North Africa, the Middle East, and throughout Europe and Asia.

Identification of Seismic Sources

Once the detections from a seismic event have been associated and an accurate location estimate has been obtained, the next step in monitoring is that of event identification. As noted above, the IDC's role in event identification is limited to providing assistance to treaty signatories. The CTBT Protocol indicates that the IDC may apply "standard event screening criteria" based on "standard event characterization parameters." To screen out an event means that the event appears not to have features associated with a nuclear explosion. If the IDC can screen out most events, then treaty states can focus attention on the remainder. For example, an event may have its depth estimated with high confidence as 50 km. Such an event would be screened out by a criterion that eliminates events confidently estimated as deeper than 10 km.

The most successful discriminants are based on the location (including the depth), and analysis of the amplitude ratio between different types of seismic wave. Location is important as a discriminant, because earthquakes are very rare (or totally unknown) in most regions of the world—for example for most of the territory of the Russian Federation. Any seismic signal from such an aseismic region will therefore attract attention and require careful scrutiny. At the opposite extreme, represented for example by much of China, earthquakes are common and there is a large population of previous earthquakes against which to compare the signals of a new event. An archive of such earthquakes will gradually be built up by IMS stations as that network becomes established. Archives already exist for numerous non-IMS stations.

Based on practical experience with teleseismic signals, there is an extensive literature on methods of discrimination between earthquakes and explosions. For example, comparison of teleseismic body-wave and surface-wave amplitudes has empirically been shown to provide an excellent discriminant. Surface waves from a shallow earthquake with the same body-wave strength as an explosion are typically 6 to 8 times larger than surface waves from the explosion. But this method usually cannot be used for events much below magnitude 4 because teleseismic surface waves are then typically too small to detect.

For teleseismic signals, a rough rule is that identification thresholds are about half a magnitude unit above detection thresholds, where detection thresholds are interpreted as in Figure 2-2 (i.e., a requirement for detection at three or more stations in order to provide a useful estimate of the location).

Practical experience with discrimination using regional signals is more limited, but growing, and the best methods are based on the use of spectral ratios of two different regional waves. In practice, the particular spectral ratio that is most effective for discrimination can be different for different regions. Discrimination has been demonstrated down to magnitude 3 for many regions. This capability requires access to data of high quality for the event of interest, and adequate data sets of previous explosions and earthquakes against which that event can be compared. Studies now underway are building up confidence in discrimination based on regional waves, for different areas of interest. In practice, a particular "problem event" in or near a region of interest has sometimes spurred the necessary special studies to enable discrimination to be done to low magnitudes using regional waves. Such was the case for a small seismic event (magnitude about 2.5) that occurred near the Novaya Zemlya test site on December 31, 1992, which after much effort lasting several months led to an improved understanding of regional waves from sources near this site, and identification of the event as a very small earthquake.

For regional waves, it appears that identification thresholds may not be significantly different from detection thresholds. This conclusion is based on the fact that for detection thresholds defined as in Figure 2-2, with detection required by at least enough stations to provide a useful location estimate, it is likely that one or more of the stations will have signal levels high enough to enable the measurement of spectral ratios suitable for discrimination. In the context of the IMS network, with detection thresholds set solely by the primary stations, auxiliary stations provide additional sources of data for measuring spectral ratios. And in the case of an event of sufficient interest to require going beyond routine analysis based only on IMS data, supplementary data from stations operated for purposes other than treaty monitoring can be used.[14] Vast regions of Europe, Asia, North America, North and South Africa, and the Middle East are currently being monitored for earthquakes down to magnitude 3 or lower by networks operated for purposes unrelated to the CTBT. There are literally thousands of seismometers deployed around the world. Their numbers are growing, as is the trend of data quality and of products derived from the data. Basic reasons for these improvements are the quality of modern hardware and software, which are replacing earlier systems; a substantial and growing infrastructure of geophysical research into Earth structure and the science of earthquakes; and general concern over earthquake hazards.

For small regions that have been intensively studied, such as former nuclear test sites, the identification threshold can be even lower than the three-station detection threshold, since just one station at regional distances can provide discrimination capability if the signals at this station are of high enough quality, even though the usual standards for obtaining an accurate location are not met. Of course it is not good to rely upon a single station (especially if it is on the territory

[14] Such stations cannot always be relied upon, their data may not be obtainable for several days, and if stations are available they must be evaluated and perhaps calibrated in an *ad hoc* fashion. But practical experience with several problem events has demonstrated that useful data from supplementary stations can often be found. In some cases they have provided the best available data for such events.

of a country where suspicious events occur), and a single station may not be regarded as adequate for building the case that a particular event should be investigated with an on-site inspection. But the overall view of monitoring capability should be developed in the context of the whole system, which may include satellite data and other non-seismic methods of monitoring, once a single (seismic) station provides evidence of the possible occurrence of a small explosion.

A preliminary result from screening studies at the PIDC is that more than 60 percent of events with magnitude greater than or equal to 3.5 are routinely screened out on the basis of a conservative interpretation of their regional-wave spectral ratios. In practice, objective screening based upon such a discriminant may be developed over a period of time and routinely applied at the IDC in ways that may have to be fine-tuned slightly differently for different regions.

Some successful methods of event identification use a combination of seismic and other data. For example, about 70 percent of all earthquakes occur under the ocean and many of these can easily be recognized as earthquakes on the basis of an absence of strong hydroacoustic signals.[15]

Mine blasting can result in seismic events smaller than magnitude 4 that may be detected and located by the IDC. These events can appear similar to small nuclear explosions using standard criteria such as depth estimates and weak surface waves. For a chemical explosion fired as a single charge at a depth sufficiently great to contain all the fractured material, there is no difference seismically from a small nuclear explosion, and no indication (as to the type of explosion) from ground deformation. But mine blasts above a few tons are in almost all cases executed for the commercial purpose of fracturing large amounts of rock, and as such they routinely consist of numerous small charges which are fired in a sequence of delays. This practice is sometimes called "ripple firing." The resulting seismic source is therefore spread out in space or time, or both, and can be identified as different from a single-fired source by use of high-frequency seismic signals. Another potential discriminant of mine blasting is the infrasound signal which can be generated by explosions used in surface mining, and which would not be expected from a small underground nuclear explosion unless it vented significantly—which, in turn, would give a very strong radionuclide signal.

Radionuclide Releases From Underground Explosions

Experience indicates that underground testing has often given rise to radioactive releases into the atmosphere, and can therefore potentially be detected by the IMS radionuclide monitoring network, which is primarily directed at monitoring atmospheric nuclear explosions (see below). Recent Russian papers documenting Soviet nuclear testing state that all underground tests at Novaya Zemlya and about half the underground tests at the Semipalatinsk test site in Kazakhstan resulted in release of radioactivity.[16] Radionuclide detection plays a significant role in the remote detection and identification of nuclear tests. A decoupled blast in the 1 to 5 kiloton region, for example, could vent significant quantities of debris proportional to the nuclear yield, irrespective of the decoupling of the seismic signal. On-site inspection, discussed below, provides the opportunity to detect, near to the test site, radioactivity that may have been generated by a nuclear explosion in amounts too small to be detectable at greater distances.

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[15] If a seismic event is located with confidence in an ocean area, it can only be an explosion if the device was set off in a hole drilled into the ocean floor, or if it was set off in the water itself. The logistics of sub-oceanic drilling to sufficient depths for containing a nuclear explosion are so formidable as to rule out this possibility in most areas. The simplest way to screen an oceanic seismic source is then to examine hydroacoustic data, noting that an explosion in the water would generate very large sound waves within the water. An absence of hydroacoustic signals can therefore screen out, as earthquakes, all seismic sources confidently located in ocean areas.

[16] For example, V.N. Mikhailov, et al., *Northern Test Site: Chronology and Phenomenology of Nuclear Tests at the Novaya Zemlya Test Site* (July 1992).

Monitoring Against Underground Evasion Scenarios

The concept of evasive testing has been extensively explored since 1959, when the best known evasive method (cavity decoupling) was first proposed, and presented by the United States at trilateral CTBT negotiations with the United Kingdom and the Soviet Union. Some of the hypothesized methods of evasive testing are intended to reduce specific types of signals from a nuclear explosion; some are intended to mask or disguise the signals by combining them with the signals from a non-nuclear source such as chemical explosions used in mining; and, as noted earlier, some methods focus on evading attribution.

The energy released by a nuclear explosion, at the level of a kiloton or more, is much greater than can be physically contained in practice by man-made structures above ground. Therefore, evasive testing in the underground environment is generally regarded as the most serious challenge to monitoring efforts.

In the era of monitoring underground nuclear tests principally by use of teleseismic signals, serious consideration had to be given to the concept of hiding a nuclear explosion by testing shortly after a large earthquake. This possibility, which faces the difficulties of preparing a test and waiting months or longer for a suitable earthquake, and of identifying and evaluating such an earthquake and carrying out the test within minutes of the earthquake's occurrence, is rendered far harder to execute by the fact that today's monitoring systems record regional seismic waves. These waves in practice are not reliably obliterated by teleseismic signals, even from the largest earthquake.

The most serious methods of evading detection and identification of an underground nuclear test are decoupling in large cavities and masking by mine blasting.

Decoupling

If a nuclear explosive device is tested in a large enough cavity, constructed deep underground, then almost all the explosive energy goes into pumping up the gas pressure within the original cavity. This contrasts with a tamped explosion, for which the energy goes into non-elastic processes such as melting and crushing rock, thus creating a new cavity and strong seismic signals. An explosion in a previously constructed cavity therefore decouples much of the energy that would have gone into seismic signals, reducing them by a so-called decoupling factor which can be as high as 70. Such an explosion is said to be "fully decoupled" if the original cavity walls are not stressed beyond their elastic limit. In practice with chemical explosions, decoupling factors of 10 to 30 have been typical.

The United States carried out a decoupled nuclear test of 0.38 kt in 1966, in the cavity created years earlier in a salt dome by a much larger nuclear explosion, and demonstrated that a decoupling factor of about 70 for a small yield is indeed possible. At a fixed depth the volume of the cavity has to increase in proportion to the yield to achieve the same decoupling factor, but as yield increases so do the practical difficulties of clandestine cavity construction and radionuclide containment.[17] The Soviet Union carried out a partially decoupled test of about 8 to 10 kt in 1976, in a cavity (in salt) of mean radius 37 m (sufficient to fully decouple about 3 kt). But this event was decoupled only by a factor of about 15, and it had magnitude about 4.1. The resulting seismic signals were picked up teleseismically as far away as Canada, and according to news reports at the time were promptly identified as originating from a decoupled nuclear test.

[17] In salt at a depth of around 1 km, the spherical cavity required for full decoupling of a 1-kt explosion has a radius of about 25 m and a surface area of about 8,000 square meters. This area, which is increased for a non-spherical cavity, would be exposed to a gas pressure of around 150 atmospheres. At a fixed yield, the volume of the cavity must be increased as the depth is decreased, in order to achieve containment.

Aspherical cavities, which are easier to construct than spherical cavities of the same volume, can also achieve high decoupling factors, but they also weaken the cavity walls by concentrating stress, making it more likely that radionuclides will be released.[18]

There is no practical experience with cavity decoupling of a nuclear explosion in hard rock, which is much more common than suitably large salt deposits. Hard rock in practice contains cracks on many length scales, and there is no experience with containing radionuclides in material that is intrinsically cracked and exposed to high gas pressures over large areas (tens of thousands of square meters). Containment is itself a highly technical subject, built up from empirical experience and learning from mistakes (for example at the Nevada test site). But key containment techniques relied upon for tamped explosions are not available for a decoupled explosion.[19]

Evaluation of the cavity decoupling scenario as the basis for a militarily significant nuclear test program therefore raises a number of different technical issues for a country considering an evasive test:

- Is there access to a region with appropriate geology for cavity construction?
- Is there such a region which is suitably remote and controllable, and that can handle the logistics of secret nuclear weapons testing?
- Can cavities of suitable size and shape and depth and strength be constructed clandestinely in the chosen region, hiding the material that has to be removed from below ground?
- Can the limited practical experience with nuclear tests in cavities in salt, and very low-yield chemical explosions in hard rock, be extrapolated to predict the signals associated with nuclear testing in cavities in hard rock?
- Can a decoupling factor as high as 70 be attained in practice for yields significantly higher than subkiloton?
- Can those carrying out the decoupled test be sure that the yield will not be larger than planned, and thus only partially decoupled?
- Can the site be chosen to avoid seismic detection and identification, given the detection thresholds of modern monitoring networks and their capability to record high-frequency regional signals?
- Can radionuclides be fully contained from a decoupled explosion?
- Can nuclear explosions of large enough yield be carried out secretly, and repeated as necessary, to support the development of a deployable weapon?
- Can secrecy be successfully imposed on all the people involved in the cross-cutting technologies of a clandestine test program, and on all the people who need to know of its technical results?

These questions represent layers of difficulty with the cavity decoupling evasion scenario, going outside practical experience in a number of areas. Most questions have been the

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[18] Stable non-spherical cavities are easier and cheaper to construct than stable spherical cavities of the same volume, and it has been demonstrated for small chemical explosions that non-spherical cavities can provide approximately the same decoupling factor as that for the spherical cavity. But for a non-spherical cavity there is a significantly greater risk of radionuclide releases because (a) the surface area is greater (than for a sphere of the same volume), and so a greater chance of the pressurized gas encountering a crack in the walls, and (b) part of the walls must be significantly nearer the device than for a device at the center of an equivalent sphere. It is this fact that places a limitation on the aspect ratio of a nonspherical cavity, because of the possibilities for ablation shock (in the case of nuclear explosions, but not chemical explosions). Such a method for transferring energy into the walls can lead to wall damage promoting radionuclide release. In addition it can lead to non-elastic deformation and hence larger seismic signal generation and a smaller decoupling factor (for a nuclear explosion).

[19] See, for example, J. Carothers, et al., *Caging the Dragon: The Containment of Underground Nuclear Explosions* (DNA Technical Report 95-74, 1995).

subject of extensive technical analyses. For some questions, the answer is clearly affirmative.[20] For other questions, there are experts in particular fields who confidently assert that particular problems can be overcome.[21] But the real issue is whether the scenario as a whole can be made to work.

Although it would appear that an uppermost bound of 7 kt (evasive) is implied by detection capability at the 100-ton level or better (tamped; see Figure 2-3), we find this 7-kt value is not plausible because of the numerous obstacles that must simultaneously be overcome. It is the whole monitoring system that has to be addressed by a potential evader. Signals would have to be hidden from the IMS, from NTM, and from numerous sensors operated for purposes unrelated to treaty monitoring. In many instances, a series of nuclear tests would be necessary to achieve a tester's objectives. For reasons such as these, it has been difficult to reach a consensus in the monitoring community on a particular value of yield that all can agree is the maximum available to a potential evader—a yield above which a test would be reliably detected and identified by some particular component of the monitoring system. Rather, the basic issue is whether the cavity decoupling scenario itself is plausible given the difficulties and risks it entails. Only nations already possessing extensive knowledge of nuclear explosive devices and with access to suitable geologic sites could expect to address the difficulties of this type of testing.

It has been claimed that cavity decoupling is plausible for evasive testing not just at the level of 1 or 2 kt, but at 20 kt, and even as high as 50 kt. Ignoring completely the challenges of cavity construction and radionuclide containment, such explosions (even if fully decoupled by a factor of 70) would have seismic signals far above the detection levels contoured in Figure 2-3.

Accepting the possibility of a cavity decoupled test, we conclude that such an underground nuclear explosion cannot be reliably hidden if its yield is larger than 1 or 2 kilotons.

Mine Masking

Another proposed evasion scenario is the use of mining operations and large chemical explosions to mask or disguise an underground nuclear explosion. A country considering this approach would need to face some of the general problems outlined above for a cavity-decoupled nuclear test, including containment of radionuclides, imposition of secrecy on many people, and the capability of seismic monitoring.

As for mine masking, chemical explosions in mines are typically ripple-fired and thus relatively inefficient at generating seismic signals compared to single explosions of the same total yield. For a nuclear explosion that is not also cavity-decoupled to be hidden by a mine explosion of this type, the nuclear yield could not exceed about 10 percent of the aggregate yield of the chemical explosion. A very high-yield, single-fired chemical explosion could mask a nuclear explosion with yield more comparable to the chemical one, but the very rarity of chemical explosions of this nature would draw suspicion to the event. Masking a nuclear yield even as large as a kiloton in a mine would require combining the cavity-decoupling and mine-masking scenarios, adding to the difficulties of cavity decoupling already mentioned.

A confidence-building measure specified in the CTBT Protocol is an attempt to address this issue: "… each State Party shall, on a voluntary basis, provide the Technical Secretariat with notification of any chemical explosion using 300 tonnes or greater of TNT-equivalent blasting material detonated as a single explosion anywhere on its territory, or at any place under its juris

[20] Thick salt deposits are known to exist for example in certain regions of Russia and the United States. Techniques have been developed for hiding material removed from underground.

[21] Large cavities in salt can be constructed by pumping in water and pumping out brine; and containment can be improved by going to greater depths—though cavity construction is then more difficult and subsequent work in the cavity is more dangerous.

diction or control." The Protocol adds that: "Each State Party shall, on a voluntary basis, as soon as possible after the entry into force of this Treaty provide to the Technical Secretariat, and at annual intervals thereafter update, information related to its national use of all other chemical explosions greater than 300 tonnes TNT-equivalent." Execution of this voluntary measure will amount to a significant effort, in that the mining industry uses megatons of chemical explosive each year (2 megatons/year in the United States alone).

If there were a nuclear explosion in a mine, and a challenge was issued to which the reply was "those signals came from a single-fired chemical explosion," pursuing the matter could be problematic insofar as, under the CTBT, information on chemical explosions is voluntary and cannot easily be checked. The basis for obtaining support for a formal on-site inspection could be difficult to develop. Again, however, the issue has to be addressed in terms of the size of a nuclear explosion that could plausibly be hidden in this way. Its magnitude would have to be somewhat lower than the biggest chemical explosions, and thus capped at about magnitude 3.5. Such yields if tamped are quite small (see Table 2-2). And so this scenario as a whole must be combined with other evasive measures, in order to reach the kiloton level.

There are two types of technical effort that can be carried out to help monitor mining regions for compliance with a CTBT. The first of these is installation of nearby seismographic stations that record digitally at high sample rates. Such data can distinguish between single-fired explosions and the multiple-fired explosions typical of mining operations. The second is provision of technical advice to mine operators so that they execute their blasting activities using modern methods of delay-firing—which have economic advantages, as well as enabling the blasting of rock in ways that do not make the large ground vibrations (and strong seismic signals) typical of old-fashioned methods of blasting.[22]

For those specific locations where mine masking remains a concern, this could be addressed with installation of infrasound and radionuclide monitoring equipment, and with site visits. Though such monitoring would be voluntary under the CTBT, it could be enhanced via bilateral agreements and/or by multilateral agreements between neighboring countries in a particular region. Such voluntary compliance would help in proving that the observed event was not a nuclear explosion.

Methods For Improving Seismic Monitoring Capability

The detection capability described in Figures 2-2 and 2-3 underlies much of the discussion above, and it is around 100 tons. If it is deemed necessary to achieve even better levels of monitoring treaty compliance (to lower yields and with greater confidence at the 100-ton level), there are a number of ways to make improvements.

(1) Capability could most simply and cost-effectively be improved by including continuous reporting from the 120 stations specified as the IMS auxiliary network. The detection capability of the IMS at present is based solely on the primary network, because continuous examination of seismic data is done only for these stations. Auxiliary stations are already recording continuously, and they already have satellite links to the IDC. If their data along with data from the IMS primary seismic network were continuously examined for detections, the monitoring thresholds shown in Figure 2-2 (three station detection capability) would drop generally by about 0.25 magnitude units in Europe, Asia, and North Africa, and by about 0.5 magnitude units in

[22] Both of these approaches are developed in National Research Council, *Seismic Signals from Mining Operations and the Comprehensive Test Ban Treaty: Comments on a Draft Report by a Department of Energy Working Group* (Washington, DC: National Academy Press, 1998). The NRC recommended an emphasis on the first approach. The DOE working group had recommended the second approach.

some regions (such as Iran, for which the detection threshold would drop from about 3.25 to about 2.75).

(2) More generally, detection capability can be improved by any augmentation of the IMS primary seismic network, to the extent that the additional data streams are continuously examined for detections, along with IMS data streams. Augmentation can be done to improve the monitoring of areas of particular interest, for example regions of thick salt, and mining regions, to the extent there is concern over evasive testing in these areas and therefore a need to monitor them to lower magnitudes.[23]

(3) In cases where a small event is suspected at a location almost the same as that in which a larger event has been documented, then correlation analysis can sometimes provide good detection of the smaller event, even though its signals are not directly apparent. Though now a specialized and little-used technique, it has proven useful for detecting aftershocks (for example of the Kara Sea earthquake of August 1997, near the Novaya Zemlya test site), and can be used to search for very small explosions near the site of recorded larger explosions. In future decades, this may become the method of choice for detection of very small events in areas for which an archive of previously recorded events becomes available.

(4) Instead of searching for detections in the continuous data stream from each IMS station separately, the data streams can be added together from different stations with an appropriate time delay, and then subjected to continuous search.[24] This method, known as Threshold Monitoring, enables continuous measurement of the maximum magnitude at which a seismic event could have occurred at a particular location and a particular time. To the extent that there is no seismic activity in the broad region, this maximum magnitude can be very low. To the extent there is activity anywhere in the region, it can raise the maximum magnitude at the site of interest even if the activity did not occur at that location.[25]

The Threshold Monitoring method is well-suited to monitoring aseismic regions down to significantly lower magnitude than conventional single-station detection thresholds. In application to Novaya Zemlya, the NORSAR organization in Norway (which pioneered the Threshold Monitoring method) has demonstrated that the maximum magnitude at which any seismic activity could have occurred is lower than 2.5 for most of the time. But this maximum magnitude can occasionally rise above 2.5 on some days, due to seismic activity in the broad region of the Barents Sea and other areas. On other days, this magnitude is closer to 2, all day. On such days, the indication from Table 2-2 relating magnitude and yield (with all the assumptions this entails) is that Novaya Zemlya can be monitored down to below 10 tons (tamped). The Threshold Monitoring method can be applied in near-real time if data are promptly transmitted to an analysis center, or with a delay to the extent that data become available from a relevant station at a later date.

(5) Numerous seismic stations operated for purposes unrelated to treaty monitoring are not currently used in ways that enable detection thresholds to be lowered. Typically, either the data are not routinely examined at each station for small amplitude detections, or such detections are not routinely reported to any international data centre. The International Seismological Cen

[23] Augmenting the already sensitive IMS primary seismic network as described in (1) or (2) would decrease the number of unassociated signals reported by the primary network alone (see footnote 13). The additional events detected at three or more stations would be of low magnitude, presenting challenges for event identification; and yet more events at even lower magnitude would still generate unassociated signals in large numbers with the augmented network. In general, augmenting a network improves monitoring capability by driving the monitoring threshold downward, but it also increases the number of unassociated signals below the threshold.

[24] The appropriate delays are different (for a given set of stations) for different source locations and for different seismic waves. Numerous different sets of delays can be selected, one for each source location, to seek evidence of small events at each source location. Knowing the noise levels at each station, it is then possible to state, for each source location, that if a seismic event occurred at a particular time, it must be below a certain magnitude.

[25] To find out where specific activity occurred, it is necessary to find detections at single stations, preferably three of them or more as in Figure 2-2.

tre (which at present receives detection information from about 3,000 stations) is potentially capable of serving the necessary role.[26] But most station operators around the world ignore the ISC; and those that do contribute detections often do not contribute them for small events. If, however, an organizing principle were agreed to by non-IMS station operators, to develop a joint bulletin describing all seismic activity down to about magnitude 3 on continents, there would be significant benefits for treaty monitoring.

Monitoring Underwater Nuclear Explosions

Underwater nuclear tests can be monitored by hydroacoustic, seismic, and radionuclide signals.

Hydroacoustic signals in oceans travel to great distances within a waveguide, sometimes called a "sound channel," so that explosions of only a few kilograms yield in most regions of the deep oceans are readily detected at distances of thousands of kilometers.[27] Such sources can be identified as explosive by detecting the presence of a characteristic bubble pulse in the recorded signal, caused by gases at the source expanding and contracting. Because hydroacoustic waves also couple efficiently into seismic waves at the ocean bottom (and vice versa), the underwater medium can be effectively monitored by a combination of hydroacoustic and seismic networks. Monitoring sound waves in the oceans is a well-advanced discipline, primarily as a result of investments in acoustic systems to detect submarines.

The hydroacoustic component of the IMS includes six hydrophone stations, each deployed in the ocean with signals sent by sea-floor cable to a nearby island for subsequent transmission by satellite to the IDC. It also includes five so-called T-phase seismic stations deployed on islands in five countries.[28] By itself this component of the IMS is not capable of locating a nuclear explosion with the desired precision. However, hydroacoustic data are useful for discrimination purposes (see footnote 15, on seismic discrimination of oceanic earthquakes) and will support seismic data used for location purposes.

Figure 2-4 shows that the yield threshold is down to just a few kilograms for most oceans in the Southern Hemisphere. Almost all the world's ocean basins will be monitored down to better than one ton.

Although coupling from explosive energy to oceanic waveguide is very efficient for the deep oceans, in the case of shallow oceans it is possible for horizontally-traveling acoustic energy to be blocked from reaching the waveguide, and hence from reaching distant hydrophones. But for explosive sources in shallow water, downward-traveling acoustic energy converts well to seismic waves at the ocean floor that can then propagate in the solid Earth. This coupling was demonstrated by two explosions in the Barents Sea, which is located north of Norway, on August 12, 2000. These explosions resulted in puncturing the hull of the Russian submarine *Kursk*. The second and larger explosion, in water about 100 m deep, was well recorded by several IMS seismic stations (both regionally and teleseismically at stations in Russia, Alaska, and Canada), and by non-IMS stations. Its magnitude was about 3.5, which according to Table 2-2 would correspond to about 100 tons tamped in hard rock, but corresponds to only a few tons yield for an explosion in water. At the IMS and non-IMS stations which recorded regional signals, correlation analysis permits clear seismic detection of the first and much smaller explosion, with yield about

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[26] This organization, with headquarters in the United Kingdom, has served research communities for decades with authoritative information on seismic source locations, estimated on the basis of detections reported voluntarily by hundreds of institutions operating seismic networks at the national or regional or local scale.

[27] A kilogram is a millionth of a kiloton.

[28] The T-phase travels horizontally from an oceanic source as a hydroacoustic wave in the water, converting to a seismic wave upon incidence at the interface between sea and land. It is then recorded on land as a seismic wave.

a hundred times smaller (i.e., a few tens of kilograms).

The IMS hydroacoustic and seismic networks are complementary for monitoring the world's oceans, in that the hydroacoustic network has highest sensitivity in the southern oceans where IMS seismic networks are weakest, and the seismic networks have high sensitivity in the northern oceans where the IMS hydroacoustic network is weakest.

Monitoring Nuclear Explosions in the Atmosphere

Nuclear tests in the atmosphere are best monitored with radionuclide, infrasound, and electromagnetic systems (including satellite-based optical detection, which is not part of the IMS). The hydroacoustic network also contributes to monitoring for atmospheric explosions above the broad ocean area. In this section we comment on the infrasound and radionuclide IMS networks.

Infrasound Monitoring

Volcanoes, meteorites, explosions, and other natural phenomena and industrial activities produce sound waves in the atmosphere that can be detected at substantial distances from the causative event. This propagation process is modified by wind and temperature variations, even though there is little attenuation at low frequencies (less than 10 Hz). There is a substantial body of knowledge regarding infrasound propagation in the atmosphere, derived in large part from monitoring hundreds of atmospheric nuclear explosions that occurred prior to the Limited Test Ban Treaty of 1963.[29] The international community decided to include an infrasound network as part of the IMS since the CTBTO does not have independent access to satellite-based methods for monitoring atmospheric testing.

The infrasound network of the IMS will consist of 60 stations in 34 countries. Several of these stations are operating as of mid-2002. The sensors are simple, though much effort is going into the development of methods to obtain spatial averaging of local atmospheric pressure variations in order to reduce wind noise. Data are collected at each field site and passed by satellite to the IDC. Because of difficulties in interpreting the arrival time of infrasound signals in terms of distance to the causative source (difficulties due to the effects of wind and temperature on sound velocity in the atmosphere), location estimates of an infrasound sound source are expected to be poor compared to those achieved for seismic events. It can be expected that even a small nuclear explosion in the atmosphere would be associated with signals derived from the capabilities of NTM of some states party to the CTBT.

Figure 2-5 shows the projected 90 percent probability of two station detection thresholds for the IMS infrasound system. It is apparent from Figure 2-5 that thresholds are below 1 kt worldwide and below 500 tons on continents in the northern hemisphere.

Radionuclide Monitoring

Radionuclides provide the most definitive identification of an event as being a nuclear explosion. They offer highly sensitive, albeit slow (multi-day) detection of atmospheric, underwater, and vented underground nuclear explosions. No naturally occurring event that might cause a seismic or acoustic signal of concern will generate a population of radionuclides that

[29] Atmospheric testing by France and China, which did not sign the LTBT, continued for several more years.

would be characteristic of a nuclear explosion. Radionuclide detection has historically been most closely associated with atmospheric nuclear explosions (fallout), but as indicated in Table 2-1, it is an essential element of the IMS for monitoring all environments except for near-space nuclear explosions. The radionuclide element of the IMS comprises a planned network of 80 stations, of which 29 were operational as of January 2002. Capability for noble gas detection (in particular, radioactive isotopes of xenon) is initially required at 40 of these stations.[30] There will also be 16 laboratories capable of performing additional analysis of samples. It appears that this IMS network will have sensitivity on a global scale far better than any radionuclide monitoring system previously available.

All of the 80 stations will have particulate samplers. These pass large volumes of air through a filter that traps particulate matter, concentrating it so that sensitive radiation detection equipment can determine the radionuclides present in the sample. The detection of anomalies in gamma-ray spectra recorded from aerosols sampled from the atmosphere triggers a notification that debris from a nuclear explosion may be present. Capability for automated detection of anomalies in gaseous xenon-isotope abundances will be a particularly sensitive and important diagnostic of a nuclear explosion.[31]

Present estimates of the sensitivity of the radionuclide detection system are 0.1 to 1.0 kilotons for a nuclear explosion on the continents and 1 to 2 kilotons in oceans. Figure 2-6 shows the probability of single-station detection for a 1-kt atmospheric explosion within 5 days. The probability of detection increases with time after the event and exceeds 90 percent nearly worldwide within 10 days. Probabilities of detection exceed 90 percent across most of Europe and Asia and exceed 50 percent over most of the southern oceans.

Even though the radionuclide system can give proof of a nuclear explosion, backtracking the path of detected radionuclides is imprecise and does not provide an accurate estimate of the explosion location.[32] Detection of the characteristic radionuclides of a nuclear explosion would trigger searches for confirming evidence, and information on the location, based on other IMS elements and on NTM.

Monitoring Nuclear Explosions in Space

Nuclear tests in space are best monitored with a variety of electromagnetic sensors, which also have a major role in monitoring explosions in the atmosphere.

Nuclear explosions in space have been suggested by test ban critics as a possible evasion technique since 1958. However, because of the technical complexity, cost, and difficulty of obtaining diagnostic data, the use of space for CTBT evasion appears highly unlikely. Nuclear explosions were conducted in space in the early 1960s by the United States and the Soviet Union to determine some of the effects of such explosions, which were very dramatic—not to learn about the explosive weapons themselves.

Nuclear explosions in space can be detected through a number of signatures: X-rays from explosions of about a kiloton can be detected at ranges exceeding 100 million kilometers,

[30] Language in the CTBT Protocol is unusually specific here, stating with respect to 80 radionuclide stations that "All stations shall be capable of monitoring for the presence of relevant particulate matter in the atmosphere. Forty of these stations shall also be capable of monitoring for the presence of relevant noble gases upon the entry into force of this Treaty." The IMS global network of radionuclide sensors has been planned to provide detection if 10 percent radioactive noble gases generated by a 1-kt underground explosion would be vented.

[31] T. Bowyer, et al, "Field Testing of Collection and Measurement of Radioxenon for the Comprehensive Test Ban Treaty," *Journal of Radioanalytical and Nuclear Chemistry* 240 (1999): 109-122.

[32] Though efforts would be made to backtrack the path taken by detected radionuclides, the nature of atmospheric transport leads to great location uncertainties.

comparable to the distance between the Earth and the Sun. Optical effects are observable from space from altitudes between sea level to 100 kilometers over extended ranges. EMP effects are produced through intense currents induced by gamma-rays in the ionosphere. In consequence of these recognized technical monitoring possibilities and the unattractiveness of space testing, a ban on explosions in space was included in the LTBT of 1963.

The CTBT, LTBT, and NPT do not incorporate monitoring of space explosions as part of an international monitoring system. Thus monitoring of space explosions depends on national technical means. Sensors involved in observing space explosions serve the dual role of treaty monitoring and detecting and locating nuclear explosions should they be used in actual combat. Deployment of monitoring equipment continues to depend on the priorities given to the treaty monitoring missions relative to other possible space payloads.

Historically nuclear explosion detection monitoring equipment was deployed from 1963 to 1984 as part of the VELA satellite program. Twelve VELA satellites were launched between 1963 and 1970.[33] Currently nuclear explosion monitoring is a secondary mission assigned to the DSP early warning satellite systems. One sensor on the DSP is provided by the Air Force and several detectors are provided by the Department of Energy. Since 1970, 18 DSP satellites have been so equipped and the lifetime of the detectors has exceeded their design span of five years. Coverage by the DSP satellites has been incomplete. The polar regions of the Earth are not covered and most other areas of the Earth are monitored by only one satellite at any one time. In 1975 nuclear-explosion monitors were added to the GPS navigational system. Currently such detectors are flown on 33 GPS satellites. Because of the orbits of the GPS satellites, the detectors fly in a rather harsh radiation environment. Current payloads include optical detectors (bhangmeters), neutron detectors, five X-ray detectors, and two gamma ray sensors.

Over the next decade an extensive replacement program has been proposed for the sensors to be carried by the follow-on satellite system planned to replace the current satellites beginning in the year 2006. This program includes:

- enhanced optical sensors (providing five times greater sensitivity than the current system)
- autonomous EMP sensors incorporating improved background discrimination
- gamma-ray and neutron detectors
- infrared sensors
- x-ray sensors
- on-board data processing

Which and how many of these improvements will be incorporated in the future is still a matter of extensive discussion because of the conflicting budgetary and other priorities assigned to the DSP and GPS payloads, and those of still other satellites.

Other space-based detectors are also deployed, some of which provide limited additional nuclear-explosion detection capability, and some of which provide technical signatures of nuclear weapon-related activities. Extensive and successful efforts are made to track all objects launched into space. All objects in orbit around the Earth that are large enough to have any role in execution of a nuclear test are also tracked.

To summarize, monitoring of space-based explosions and of atmospheric explosions from space is based on powerful technologies which, provided they continue to be deployed and maintained as needed for this mission, will make it extremely unlikely that such testing can be

[33] In 1979, signals received from a VELA satellite indicated a possible clandestine test of a nuclear weapon in the South Atlantic or southwest Indian Ocean. Disagreement persists on whether or not such a test occurred, although the most recent review available (1994) concludes that it did not. The disagreement is due in part to limitations of the instrumentation available at that time. Today's instrumentation for detecting nuclear weapons tests in the atmosphere is sufficiently improved to enable unambiguous interpretation of such events.

conducted without being detected and identified. Attribution might require additional information, such as from use of NTM to interpret missile-launch activities.

The Role of Confidence-Building Measures and On-Site Inspections

Confidence-building measures have already been mentioned in the context of potential problems with mine blasting. The CTBT also specifies that confidence-building measures assist in calibration of IMS stations; and that each State Party undertakes to cooperate with the CTBTO and other states party to the treaty, in carrying out chemical calibration explosions or to provide relevant information on chemical explosions planned for other purposes. A number of information exchanges (between the United States and Russia) and chemical calibration explosions (in Russia and Kazakhstan) have already been carried out, contributing to IMS station calibration.

The CTBT provides for challenge on-site inspections to clarify whether or not an underground nuclear explosion has occurred. Any party to the treaty can request an inspection based on objective information from the IMS and/or National Technical Means (e.g., reconnaissance satellite photographs). The request must give approximate coordinates of the alleged event and proposed boundaries of the area to be inspected (see discussion of event location above). Authorization of an on-site inspection, which is governed by a fast-moving schedule in order to seek evidence that may diminish with time, requires a positive vote by at least 30 of the 51-member Executive Council of the CTBTO.

Inspectors can carry out a range of activities, including measurement of: aftershocks (to help distinguish between earthquake and explosion, and to increase the precision of location); radioactive noble gases or debris (such as argon-37 and krypton-85), which often escape through small cracks following an underground nuclear explosion; surface and vegetation changes due to spallation;[34] and human artifacts characteristic of test activity. While it is impossible to quantify the likelihood that any of these techniques would succeed, a violator would not be able to anticipate how to conceal all potential evidence. If the inspection determined the precise location of a suspect explosion (e.g., by aftershocks), drilling could be undertaken, which if it reached the explosion cavity would be able to obtain an unambiguous sample of radionuclides.

The question has been raised whether the Executive Council would ever give 30 votes to approve an on-site inspection, given the high political stakes involved. It is our opinion that, if a strong case were presented in relation to a "state of concern," an inspection would be approved. Gaining approval for an inspection of a Nuclear-Weapon State or other major powers could present a problem. States that have not conducted a test would presumably welcome the opportunity to clear themselves, if they had not already done so by the preliminary consultations for which provision is made in the treaty.

The more difficult question is whether any country that had actually tested clandestinely would ever permit an inspection. However, refusal in the face of a strong case of possible violation would probably be generally accepted as tacit admission of a violation. In this case, as in the case of unambiguous proof of a violation, the CTBT Conference of States Parties or the Executive Council can bring the issue to the attention of the United Nations for action.

Finally, the question arises as to whether there will be so many unidentified (hence potentially suspicious) small events at the threshold of detection that the system will be overwhelmed with challenges. In reality, given the cost of inspections and the financial and other

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[34] Spallation of the ground surface above an underground explosion occurs when the waves generated by the explosion cause surface materials to be thrown upward and then fall back under the influence of gravity.

penalties for "frivolous or abusive" requests, as specified in Article IV of the Treaty, it is unlikely that there will be many challenges without strong objective evidence.

In summary, the right of on-site inspection provided by the CTBT constitutes a deterrent to treaty violation whether or not the inspection actually takes place, and it provides a mechanism for the innocent to clear the record.

Research and Development in Support of CTBT Monitoring

Following the first CTBT negotiations, the need to develop a scientific basis for monitoring nuclear testing in all environments was explicitly recognized in 1959. This recognition led to programs of basic and applied research that continue to this day. Monitoring capability has steadily improved as global networks were installed beginning in the 1960s, and as instrumentation and methods of analysis have continued to improve. Safeguard D states that "The United States shall continue its comprehensive research and development program to improve its capabilities and operations for monitoring the Treaty."[35]

The four different monitoring technologies now used by the IMS can all be expected to continue to improve over the coming years.

- Hydroacoustics is well advanced because of work on detection of submarines, but there has been less research on transient signals and still less on the use of hydroacoustic signals to monitor underground and atmospheric explosions. Work is needed in source excitation theory for diverse ocean environments, particularly for earthquakes, and for acoustic sources in shallow coastal waters and low altitude environments. A quantitative understanding of ocean-land and land-ocean coupling would assist in the interpretation of T-phases.
- Infrasound was a recognized research field in the 1950s and up to the early 1970s, but the reduction in atmospheric testing has led almost to the elimination of infrasound studies in the United States over the last 20 years. The IMS system will establish a global array of infrasound sensors to enable routine monitoring of low-frequency sound waves on a global basis for the first time in decades. Research issues associated with CTBT monitoring involve first-order questions about the background noise, involving wind noise reduction and the nature and frequency of events such as volcanic explosions, meteor impacts, and other natural sources. Practical questions arise on the infrasound detectability of mine blasts. Basic information on U.S. monitoring experience has been released and is systematically helping to enhance monitoring capability.[36] But building up the necessary infrastructure to enable effective operation of the IMS network will take several years of support.
- The IMS radionuclide network is far more sensitive and spatially comprehensive than previous networks have been, but its infrastructure can be improved in order to support more effective operations. In addition, there is an opportunity to involve the vigorous research community in atmospheric chemistry, which has for the most part not been engaged in the technical work of improving treaty monitoring. There is considerable potential for mutually reinforcing efforts on the part of the basic-science and treaty-monitoring communities.
- Seismic research on CTBT monitoring is largely engaged in the interpretation of regional waves, with two goals: developing practical methods to improve estimates of event loca

[35] White House, Office of the President, September 22, 1997.

[36] Some very interesting infrasound signals have been received over the years, for example from incoming bolides, which on average impact the atmosphere once a month with energy of a kiloton or more.

tion based on detection of regional waves at IMS stations, and improving methods of event identification using differences between the regional waves excited by earthquakes and explosions. Steady improvements in knowledge of Earth structure can be expected to result in improvements in the accuracy of event location. The development of methods for interpreting seismic waveforms will continue to improve methods of determining the depth of earthquakes, most of which are deeper than 10 km. Events determined to be at this depth, or greater, can only be earthquakes.

Conclusions on CTBT Monitoring Capability

Detection, identification, and attribution of nuclear explosions rest on a combination of methods, some being deployed under the International Monitoring System established under the CTBT, some deployed as National Technical Means, and some relying on other methods of intelligence collection together with openly-available data not originally acquired for treaty monitoring. The following conclusions presume that all of the elements of the IMS are deployed and supported at a level that ensures their full capability, functionality, and continuity of operation into the future.

In the absence of special efforts at evasion, nuclear explosions with a yield of one kiloton or more can be detected and identified with high confidence in all environments. Specific capabilities in different environments are as follows:

- Underground explosions can be reliably detected and can be identified as explosions, using IMS data, down to a yield of 0.1 kilotons (100 tons) in hard rock if conducted anywhere in Europe, Asia, North Africa, and North America. In some locations of interest such as Novaya Zemlya, this capability extends down to 0.01 kiloton (10 tons) or less. Depending on the medium in which the identified explosion occurs, its actual yield could vary from the hard rock value over a range given by multiplying or dividing by a factor of about 10, corresponding respectively to the extremes represented by a test in deep unconsolidated dry sediments (very poor coupling) and a test in a water-saturated environment (excellent coupling). Positive identification as a *nuclear* explosion, for testing less than a few kilotons, could require on-site inspection unless there is detectable venting of radionuclides. Attribution would likely be unambiguous.
- Atmospheric explosions can be detected and identified as nuclear, using IMS data, with high confidence above 500 tons on continents in the northern hemisphere and above one kiloton worldwide, and possibly at much lower yields for many sub-regions. While attribution could be difficult to determine based on IMS data alone, evaluation of other information (including that obtained by NTM) could provide an unambiguous determination.
- Underwater explosions in the ocean can be reliably detected and identified as explosions, using IMS data, at yields down to 0.001 kiloton (1 ton) or even lower. Positive identification as a nuclear explosion could require debris collection. Attribution might be difficult to establish unless additional information was available, as it might be, from NTM.
- Explosions in the upper atmosphere and near space can be detected and identified as nuclear, with suitable instrumentation, with great confidence for yields above about a kiloton to distances up to about 100 million kilometers from Earth. (This capability is based on the assumption that relevant instruments that have been proposed for deployment on the follow-on system for the DSP satellites will in fact be funded and installed.) Such evasion scenarios are costly and technically difficult to implement. If they materialize, attribution will probably have to rely upon NTM, including interpretation of missile launch activities.

The capabilities to detect and identify nuclear explosions without special efforts at evasion are considerably better than the "one kiloton worldwide" characterization that has often been stated for the IMS.[37] If deemed necessary, these capabilities could be further improved by increasing the number of stations in networks whose data streams are continuously searched for signals.

In the history of discussions of the merits of a CTBT, a number of scenarios have been mentioned under which parties seeking to test clandestinely might be able to evade detection, identification, or attribution. With the exception of the use of underground cavities to decouple explosions from the surrounding geologic media and thereby reduce the seismic signal that is generated, none of these scenarios for evading detection and/or attribution has been explored experimentally. And the only one that would have a good chance of working without prior experimentation is masking a nuclear test with a large chemical explosion nearby in an underground mine. The experimentation needed to explore other approaches to evasion would be highly uncertain of success, costly, and likely in itself to be detected.

Thus, the only evasion scenarios that need to be taken seriously at this time are cavity decoupling and mine masking. In the case of cavity decoupling, the experimental base is very small, and the signal-reduction ("decoupling") factor of 70 that is often mentioned as a general rule has actually only been achieved in one test of very low yield (about 0.4 kiloton). The practical difficulties of achieving a high decoupling factor—size and depth of the needed cavity and probability of significant venting—increase sharply with increasing yield. And evaders must reckon with the high sensitivity of the global IMS, with the possibility of detection by regional seismic networks operated for scientific purposes, and with the chance that a higher-than-expected yield will lead to detection because their cavity was sized for a smaller one.

As for mine masking, chemical explosions in mines are typically ripple-fired and thus relatively inefficient at generating seismic signals compared to single explosions of the same total yield. For a nuclear explosion that is not also cavity-decoupled to be hidden by a mine explosion of this type, the nuclear yield could not exceed about 10 percent of the aggregate yield of the chemical explosion. A very high-yield, single-fired chemical explosion could mask a nuclear explosion with yield more comparable to the chemical one, but the very rarity of chemical explosions of this nature would draw suspicion to the event. Masking a nuclear yield even as large as a kiloton in a mine would require combining the cavity-decoupling and mine-masking scenarios, adding to the difficulties of cavity decoupling already mentioned.

Taking all factors into account and assuming a fully functional IMS, we judge that an underground nuclear explosion cannot be confidently hidden if its yield is larger than 1 or 2 kilotons.

Evasion scenarios have been suggested that involve the conduct of nuclear tests in the atmosphere or at the ocean surface where the event would be detected and identified but attribution might be difficult. NTM of the United States and other nations might provide attribution, without being predictable by the evader.

The task of monitoring is eased (and the difficulty of cheating magnified), finally, by the circumstance that most of the purposes of nuclear testing—and particularly exploring nuclear-weapon physics or developing new weapons—would require not one test but many. (An exception would be the situation in which an aspiring nuclear-weapon state had been provided the blueprints for a weapon by a country with greater nuclear-weapon capabilities, and might need only a single test to confirm that it had successfully followed the blueprints.) Having to conduct multiple tests greatly increases the chance of detection by any and all of the measures in use, from the IMS, to national technical means, to sensors in use for other purposes.

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[37] See, for example, the United Nations Conference on Disarmament Working Paper CD/NTB/WP.225 (Geneva, 1995).

It can be expected, in future decades, that monitoring capabilities will significantly improve beyond those described here, as instrumentation, communications, and methods of analysis improve, as data archives expand and experience increases, and as the limited regions associated with serious evasion scenarios become the subject of close attention and better understanding