Seismology and CTBT Verification

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It is well-known that the design and production of nuclear weapons required major efforts in scientific research and engineering, with a supporting infrastructure of weapons laboratories. Less well-known, is that scientific research and development have also played an important role in nuclear arms control. In this paper, my purpose is to explain the role of seismology in treaty verification; to describe what seismology (and associated infrastructures) can and cannot do using monitoring systems now in place; and to give a sense of what can be expected with likely future improvements.

Seismology is the study of how the ground moves, not just for strong earthquakes like that which severely damaged the Stanford University campus in October 1989, but for ground motions that can be detected even a billion times smaller, caused by earthquakes and explosions which may originate on the other side of the world. Each earthquake or explosion sends out a mixture of different types of seismic waves, and for decades seismologists have been interpreting these signals in order to characterize the seismic source. Seismology has overlapping infrastructures to study the internal structure of our planet, to study earthquake hazard, and to monitor explosions.

Seismology became particularly important as a monitoring technology following the Atmospheric Test Ban Treaty of 1963, because nuclear testing moved underground and was found to generate easily-detectable seismic signals, observed all over the world for most nuclear tests. On average, about one nuclear explosion a week was carried out underground from the early 1960's to the early 1990's. Underground nuclear testing became an integral part of the process by which new nuclear weapons were designed and certified as ready for deployment --- and seismology was built up as a practical science because it became a principal means to learn of the developing nuclear weapons capability of a potential adversary. It was also recognized to be an arms control technology for monitoring compliance with an eventual ban on nuclear testing.

The CTBT will in practice be the subject of three types of seismic monitoring, namely:

- that carried out directly by an International Data Centre (IDC) using data contributed by the International Monitoring System (IMS), associated with the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) in Vienna;
- that carried out by National Technical Means (NTM), i.e. the procedures established unilaterally by various countries using any information available to them, with all countries having rights[1] to use objective information from NTM as a basis for requesting an on-site inspection; and
- that carried out by numerous private or national organizations, each acquiring and/or analyzing data of some relevance to CTBT monitoring.

In this paper I concentrate on the first type of monitoring --- the work of the IMS and IDC --- since this provides a base upon which other contributions can improve. From the IDC, IMS data is sent on request to National Data Centres/Centers. The US National Data Center is operated by the US Air Force.

The third of these types of monitoring, associated with what the CTBT calls supplementary data[2], can be important, for example in confidence-building measures and as a source of much basic information and many skills needed by the IMS and IDC. Hundreds of different institutions operate seismometers of various types. Vast regions of North America, Europe, the Western Pacific, and parts of Central Asia, Northern and Southern Africa and the Middle East are now being monitored closely for earthquake activity down to magnitude 3 or lower, by organizations whose data and methods of analysis are freely available. It is from this type of earthquake monitoring, and from field programs to study Earth structure, that geophysicists have acquired their knowledge of seismic signals in different regions; and familiarity too with the differences between signals from earthquakes and from blasting associated with the mining, quarrying, and construction industries. Seismology is still a growing science, likely to be driven indefinitely by the need to understand and mitigate earthquake hazards. Individual earthquakes can still kill many thousands of people, and they are one of the few catastrophic phenomena capable of matching the trillion dollar levels of damage a single nuclear weapon can inflict. Explosion monitoring for the CTBT will be greatly improved in the long term by cross-fertilization between the earthquake monitoring and explosion monitoring communities.

The work of monitoring for underground nuclear explosions using seismological methods can be broken down into the separate steps of:

- detecting seismic signals and grouping all the signals associated with a

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[1] CTBT Article IV, ¶34 and ¶37.

[2] CTBT Article IV, ¶27 and ¶28.

particular seismic source;

- estimating the location of that source, and the uncertainty in the location; and
- identifying the seismic source (whether earthquake or explosion), together with estimating the source size. The role of the IMS, vis-à-vis 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."[3] The responsibility of identification is left to each State Party, but the IDC assists by carrying out a process called event screening, described below.
- Seismology also plays a role in on-site inspections and in confidence-building measures.

DETECTION OF SEISMIC SIGNALS

The CTBT Protocol lists 50 IMS sites around the world at which either a three-component seismographic station[4] or an array of seismometers[5] is to be operated, sending uninterrupted data by satellite to the International Data Centre (IDC). These 50 stations constitute the primary network. Much experience is now available from a network of similar size and including many of the IMS stations. It has operated full-time since 1995 January 1, initially as part of a technical test known as GSETT-3, carried out under the auspices of the Geneva-based Conference on Disarmament which negotiated the text of the CTBT[6]. The GSETT-3 IDC, based near Washington, DC, became the Prototype IDC (PIDC) shortly after the CTBT was opened for signature in 1996, and served for five years as the testbed for many procedures that were taken up by the Vienna-based IDC in February 2000.

For seismic sources whose signals are detected by the primary network, and for which the location estimate and other attributes of the source are likely to be better quantified if additional signals are acquired, the CTBT Protocol lists an additional 120 IMS sites around the world at which either a three-component seismographic station or an array is to be operated. These stations, constituting the auxiliary network, are to operate continuously; but their data is sent to the IDC only

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[3] CTBT Protocol, Part I, ¶20(c).

[4] In order to characterize ground motions completely at a single site, they are usually recorded in the vertical direction and two horizontal directions (north, and east). Hence the term "three-component."

[5] An array of seismometers consists typically of ten to thirty separate instruments, installed over a region several square km. in area. Somewhat similar in operation to a directional microphone, an array of seismometers can pick up weaker signals than a conventional seismographic station. An array can also be used to measure the direction from which a seismic signal arrives.

[6] GSETT-3 is an acronym for the Group of Scientific Experts Technical Test #3.

for time segments that are requested by a message from the IDC. Much experience with such an auxiliary network, of somewhat smaller size, has now been acquired by the PIDC.

From January 1995 to February 2000 when operations transferred to Vienna, the IMS stations grew from about one-half up to two-thirds of the intended 50-station primary network, and reached approximately one-half of the intended 120-station auxiliary network. During this five-year time period, 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 (REB), typically published three to five days in arrears, listing the events that have occurred that day, including location estimates, magnitudes, a map of the reporting stations for each event, and arrival times of detected phases at these stations. About fifty events per day have been reported on average, with some wide variations, for a total of about 100,000 events included in the REB over its first five years. Nuclear explosions carried out by France and China (prior to their signing the treaty in 1996) were well recorded, as were nuclear explosions of India and Pakistan in 1998.

What then is the current detection capability of the IMS seismographic network, and what is its expected capability when the network is eventually completed?

The design capability of the primary network has not been formally specified. The short answer is often given, that the IMS can be expected to provide data adequate to monitor for underground explosions down to about magnitude 4. For an explosion executed in the usual way without making special efforts at concealment, magnitude 4 corresponds to a yield of approximately half a kiloton. In practice, however, the detection threshold appears to be better than magnitude 4 for regions where the IMS is complete --- and even where it is incomplete.

This tentative conclusion emerges from several lines of argument. First, from looking at an earlier network to which the modern IMS network is roughly comparable, we find that GSETT-3 was planned[7] to have a threshold detection capability in the magnitude range below 3 for large parts of Eurasia and North America. (It was above magnitude 3.4 in some continental areas of the southern hemisphere, and above magnitude 3.8 in parts of the southern oceans.) Second, in technical reports[8] that have mapped the value of magnitude at which three or more IMS stations have a high probability of detecting signals, we find that virtually

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[7] See CD/1254, a paper of the Conference on Disarmament.

[8] For example, the NORSAR semi-annual report of May 1998, pp. 72 - 88.

all of Eurasia and North America lies in zones with magnitude less than 4. Third, in certain areas of particular interest, which include the former test sites in Nevada for the U.S. and in Novaya Zemlya for the Russian Federation, the IMS seismographic network is now essentially complete and has a detection capability that is typically below magnitude 2.5. (The IMS station nearest to the Chinese former test site at Lop Nor is an array in Kazakhstan, at a distance of less than 800 km. It was opened last month, and can be expected to provide detections down to low magnitudes for Western China.) Finally, there are specific examples to show that the IMS is providing data adequate to characterize small seismic sources that are located in regions where the IMS is far from complete.[9]

LOCATION OF SEISMIC SOURCES

The CTBT Protocol, Part II, ¶3, states that

"The area of an on-site inspection shall be continuous and its size shall not exceed 1000 square kilometers. There shall be no linear dimension greater than 50 kilometers in any direction."[10]

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. It is a challenge, because for earthquakes and explosions below magnitude 4, there may not be enough detections at IMS stations for an accurate estimation of the location by the IDC, using current procedures.

The challenge is being met by a series of international activities that have successfully demonstrated in northwestern Europe how improvements in location accuracy can be obtained. These methods are now being systematically applied to other regions of Eurasia, to North America, and to Northern Africa.

IDENTIFICATION OF SEISMIC SOURCES

After an accurate location estimate has been obtained, the next step in

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[9] A chemical explosion of 0.1 kiloton took place on August 22, 1998, at the former Soviet nuclear test site in Eastern Kazakhstan. In this region of Central Asia there are several IMS stations which are not yet operational, but the explosion was well located on the basis of detections at stations far away in Sweden, Norway, Scotland, Central Africa and Alaska, as well as at three nearer stations in Russia. The explosion took place under a joint US-Kazakhstan program to destroy facilities at the former test site. It was a very unusual seismic event, since chemical explosions at depth that fire 100 tons all once, essentially in the way that small underground nuclear explosions have been fired in the past, are now very rare.

[10] A circle of radius 18 kilometers (about 11 miles) has an area around 1000 square kilometers.

monitoring is that of event identification. A review of the best technical methods for carrying out this step is given, for example, by a 1988 report of the Office of Technology Assessment[11]. But the actual identification of an event as possibly being a nuclear explosion and hence a treaty violation, perhaps warranting a request for an on-site inspection, entails judgements that bring in political as well as technical assessments. Therefore, as noted above, the IDC's role in event identification is limited to providing assistance to states party to the treaty, rather than actually making an identification. The CTBT Protocol states 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. The underlying idea is that if the IDC can screen out most events, then states party to the treaty can focus their attention on the remaining events. For the present paper, a few examples must suffice to demonstrate how methods of identification can become the basis of standard screening by the IDC.

The most successful discriminants are an interpretation of the location (including the depth), and a comparison of the magnitude of two different types of seismic waves.

About 70% of all earthquakes occur under the ocean. But 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 column. 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, because an explosion in the water column 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.

An event may have its depth estimated with high confidence as, say, 50 km. Such an event would be screened out, by a practical criterion that "events confidently estimated as deeper than 10 km are not of concern."

A screen based on comparison of magnitudes exploits the fact that shallow earthquakes are far more efficient than nuclear explosions in exciting long-period surface waves, for events with comparable short-period compressional-waves. In a preliminary study of PIDC data, about 80% of shallow events (but no nuclear explosions) were successfully screened out by the quantitative comparison of magnitudes.[12]

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[11] U.S. Congress (1988). "Seismic Verification of Nuclear Testing Treaties," OTA-ISC-361, Office of Technology Assessment, Washington, DC, US Government Printing Office.

[12] Results reported at a Workshop on Discrimination sponsored by the Defense Threat Reduction

Depth estimates, and measurements of seismic magnitudes, can be based upon so-called teleseismic waves which travel deeply in the Earth and reach distances more than 1500 kilometers. In practice it is important also to develop discriminants, and their specific application as screens, for events too small to be well-characterized teleseismically. One example is the use of high-frequency spectral ratios between different types of seismic waves that travel only at shallow depths. Hartse et al.[13] and Kim et al.[14] have shown in practice that such ratios are abnormally high for small underground explosions as compared to shallow small earthquakes, and this discriminant can be applied successfully down to magnitude 3 and possibly even smaller. The preliminary result of this method applied to PIDC data is that more than 60% of events with magnitude 3.5 or greater are screened out on the basis of spectral ratios[15]. In practice, objective screening based upon such a discriminant will likely be developed and routinely applied at the IDC in ways that may have to be fine-tuned slightly differently for different regions.

Below magnitude 4, mine-blasting can result in seismic events detected and located by the IDC, which appear similar to small nuclear explosions using criteria such as depth estimates, weak surface waves, and high spectral ratios. Hedlin et al.[16], Kim et al.[17] and others have found characteristic spectral interference patterns for such events, caused by the fact that commercial blasts routinely consist of numerous small explosions which are fired in a sequence of delays. The resulting seismic source is spread out in space and time, and is therefore very different from a single-fired nuclear explosion. Another potential discriminant of mine-blasting is the infrasound signal which can be generated by such sources[18], and which would not

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Agency, Kansas City, June 2000.

[13] Hartse, H.E., Taylor, S.R., Phillips, W.S., and Randall, G.E. (1997). Preliminary study of seismic discrimination in central Asia with emphasis on western China, Bull. Seism. Soc. Amer., 87, 551-568.

[14] Kim, W.-Y., Aharonian, V., Lerner-Lam, A.L., and Richards, P.G. (1997). Discrimination of earthquakes and explosions in Southern Russia using regional high-frequency three-component data from the IRIS/JSP Caucasus network, Bull. Seism. Soc. Amer., 87, 569-588.

[15] See footnote 12.

[16] Hedlin, M.A., Minster, J.B., and Orcutt, J.A. (1989). The time-frequency characteristics of quarry blasts and calibration explosions recorded in Kazakhstan, USSR, Geophys. J. Int., 99, 109-120.

[17] Kim, W.-Y., Simpson, D.W., and Richards, P.G. (1994). High-frequency spectra of regional phases from earthquakes and chemical explosions, Bull. Seism. Soc. Amer., 84, 1365-1386.

[18] Hagerty, M. T., Kim, W. Y., and Martysevich, P. (2000). Infrasound detection of large mining blasts in Kazakstan, in press, Pure and Appl. Geophys.

be expected from a small underground nuclear explosion unless it vented significantly --- which, in turn, would likely result in a characteristic radionuclide signal. New discriminants for particular types of small seismic events continue to be developed, both in field projects with specially deployed monitoring equipment, and in subsequent adaptation for candidate screening methods to be applied at the IDC to IMS data.

From the above examples, it may be appreciated that an underlying difficulty in treaty monitoring is making the trade-off between simple methods of analysis that are robust, objective, unchanging, and easily explained to people who lack technical training; and those more sophisticated methods which are demonstrably more effective but that require a greater degree of expert judgement and which will surely change from year to year as methodologies improve. The very existence of so much practical and specialized experience (coming from the decades of monitoring nuclear weapons tests), and of so many seismological resources generating potentially useful data, fundamentally enhances CTBT monitoring capability.

EVASION SCENARIOS

If a nuclear explosion is conducted deep underground (depth around 1 km) at the center of a large spherical cavity in hard rock, with radius greater than or equal to about 25 meters times the cube root of the yield in kilotons, then the seismic signals can be reduced by a so-called decoupling factor that may reach up to about 70. It is easier to build cavities of the same volume that are elongated rather than spherical, and such aspherical cavities can also achieve high decoupling factors, but they also increase the concentration of stress on the cavity and can make it much more likely that radionuclides will be released into the atmosphere and be detected by the radionuclide monitoring network of the IMS. An overall evaluation of the cavity decoupling scenario therefore raises a number of different technical issues:

- Does a country considering an evasive test have access to a suitably remote and controllable region with appropriate geology for cavity construction?
- Can the site be chosen to avoid seismic detection and identification (recognizing that seismic events are routinely reported down to about magnitude 3 by earthquake monitoring agencies for many areas in industrialized countries, and many countries routinely monitor neighboring territory)?
- Can cavities of suitable size and shape and depth and strength be constructed clandestinely in the chosen region, with disposal of the material that has to be removed from below ground?
- Can nuclear explosions of suitable yield be carried out secretly in sufficient number to support the development of a deployable weapon? (This question covers

numerous technical issues, including the ability to ensure the yield will not be larger than planned; and to keep all yields of a test series large enough to learn from, yet small enough to escape identification.)

- Can radionuclides be fully contained from a decoupled explosion?

Each of these questions has been the subject of extensive technical analyses.

My own opinion is that it is technically possible to address a few of these issues in a clandestine program in isolation from the others, but mastery of all these issues combined could not be achieved except possibly by a full-blown multi-billion dollar effort by a nation that already had practical experience with underground nuclear testing. Such a nation would have little to learn technically, much to lose politically, and the treaty evasion program would still be at great risk of discovery since multi-billion dollar efforts intrinsically attract attention in the modern world.

Another evasion scenario is the use of mining operations and large chemical explosions to mask or disguise an underground nuclear explosion. There is a limit on the yield of any nuclear explosion that could be hidden in this way. Chemical explosions are almost always delay-fired at shallow depths, so they are inefficient in generating seismic signals, relative to nuclear explosions that are tamped[19]. It therefore appears that only a limited number of mines with the largest blasting operations are conceivably candidates for hiding militarily significant efforts at CTBT evasion.

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.

Addressing the reality of how the IMS and State Parties will handle large blasting operations --- or the occasional single-fired chemical explosion (whose seismic signals may indeed look just the same as those of a small nuclear explosion), the treaty states that[20]

"In order to... [c]ontribute to the timely resolution of any compliance concerns

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[19] Khalturin, V.I., Rautian, T.G., and Richards, P.G. (1998). The seismic signal strength of chemical explosions, Bull. Seism. Soc. Amer., 88, 1511-1524.

[20] CTBT Article IV, ¶68.

arising from possible misinterpretation of verification data relating to chemical explosions... each State Party undertakes to cooperate with the Organization and with other State Parties in implementing relevant measures.... "
These measures provide, on a voluntary basis, information on single-fired chemical explosions using 300 tons or more of TNT-equivalent blasting material; and information on mine blasting (such as mine locations) for all other chemical explosions greater than 300 tons TNT-equivalent.

To the extent that mine blasting remains a serious concern, problems can be addressed with nearby installation of infrasound and radionuclide monitoring equipment, and with site visits. These activities would be voluntary under the CTBT. Potentially they could also be made the subject of mandatory bilateral agreements, and/or multilateral agreements between neighboring countries in a particular region.

Some remarkable assessments of evasion scenarios were presented in the U.S. Senate debate of October, 1999, leading up to the negative vote on CTBT ratification. Thus, the Senate majority leader stated in executive session that "a 70-kiloton test can be made to look like a 1-kiloton test, which the CTBT monitoring system will not be able to detect." He was referring to the decoupling scenario. Treaty opponents gave speeches which included exactly the same sentence: "While the exact thresholds are classified, it is commonly understood that the United States cannot detect nuclear explosions below a few kilotons of yield." It was also stated that "Advances in mining technologies have enabled nations to smother nuclear tests, allowing them to conduct tests with little chance of being detected."

Let us address each of these three statements in turn.

70 kilotons would be an enormous explosion, about twice the energy of the combined Hiroshima and Nagasaki bombs, and would indeed be of military significance. The cavity that conceptually might reduce signals from a test of this size to something comparable to 1 kiloton would have to be deep underground (on the order of 1 km deep), with volume equal to that of a sphere 200 m in diameter. Such a spherical cavity could not be built in practice, not even in the open, let alone in secret. Just supposing it could be built, almost all the 70-kiloton energy released by the test would go into pumping up gas in the cavity to about 150 times normal atmospheric pressure. These gases would be radioactive, and the high pressure means they would leak through cracks that inevitably would exist in the 125,000 square meters or more of cavity wall (i.e., about 35 acres), even if the cavity did not collapse. Distant radionuclide sensors of the IMS would detect the test if only 0.1%

of the radioactivity escaped. The small fraction of energy released as seismic signals, if comparable to those from a typical (well-coupled) 1 kiloton test, would travel far beyond the rock surrounding this hypothetical (impossible-to-construct) cavity, and would be large enough for detection at numerous seismometers all over the world, including those of the CTBT monitoring system.[21]

As for the United States not being able to "detect nuclear explosions below a few kilotons of yield", this might have been an accurate representation of the state of affairs in about 1958 when CTBT negotiations began. But it is more than 40 years later. Unclassified arrays of seismic instruments continuously and routinely monitor vast areas of the globe for earthquakes and explosions down to low seismic magnitudes, for example reaching down to about magnitude 2 to 2.5 at Russia's former nuclear test site on Novaya Zemlya. This capability translates into the ability to detect down to about 0.01 kilotons of well-coupled yield.

As for mining technologies, the overall trend of modern methods of mine blasting has resulted in general in smaller seismic magnitudes than prevalent a few decades ago. There are only a limited number of mining regions where signals from a small (~ 0.1 kiloton) nuclear test could be masked by a simultaneous mineblast without taking the additional steps of putting the nuclear test in a cavity --- which would be associated with the complications listed above[22].

To summarize this section: if concern over evasion scenarios is sufficient that problems are targeted for resolution, then the goal of "... monitoring ... nuclear explosions down to a few kilotons yield or less, even when evasively conducted" (the U.S. position quoted in CD/NTB/WP.53 of 18 May 1994) is achievable.

CONCLUDING REMARKS

Any discussion of monitoring thresholds for a CTBT is a tacit acknowledgement that monitoring of this zero yield treaty cannot be done at low enough levels of yield. Seismology, and other technologies, must be deployed with sufficient resources by well-qualified people, to drive down to military insignificance the levels of yield at which tests have a reasonable chance of being hidden.

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[21] A specialized issue here, is the question of how big a suitably deep cavity can be built, clandestinely, in salt domes or thick layers of salt --- since this is by far the easiest material to use for such construction. To the extent that there is sufficient concern over this issue, it can potentially be addressed by bilateral or multilateral agreements to monitor such regions down to low magnitude. This type of geology has few earthquakes, and a potential treaty evader would know that any seismic activity would arouse attention.

[22] Regions of mine-blasting with unusually large seismic signals, to the extent they are of concern, could also be made the subject of special monitoring.

The work of monitoring the CTBT by seismological methods will be demanding, because of the technical difficulty and the scale of organizational effort that is necessary, and because of the need to interact with political and bureaucratic decision-making. Evaluations of CTBT monitoring capability may be carried out as part of the domestic ratification process in each of the different signatory States. Such evaluation during the U.S. Senate debate of October 8, 12--13, 1999 relied upon a series of unsupported assertions. Evaluations are carried out from time to time, together with budgetary review, by government agencies, not all of them eager to put resources into a major initiative in nuclear arms control. A review of nuclear explosion monitoring has not been carried out in the U.S. political arena since the 1980's (see footnote 11).

The work of treaty monitoring is enhanced by the existence of major seismological resources other than the IMS primary and auxiliary networks and the IDC. This point is acknowledged in the CTBT and its Protocol, which make several references to the need to take national monitoring networks into account. National networks are increasing in number and quality[23]. They are associated with the production of detailed bulletins of regional seismicity that typically are intended to meet objectives in the study of earthquake hazard. Such bulletins, and easy access to the underlying digital seismogram data, can be very helpful in CTBT monitoring, for the study of problem events and for improving the IDC's routine seismicity bulletins. It is to be expected that the background of earthquakes will provide a means of calibration to achieve more accurate location of all seismic events. Seismology is continuing to provide new methods of data acquisition and data analysis, giving useful information that will improve the work of the IMS, assisting in the attainment of national and international monitoring goals for a CTBT.

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[23] For example, a major upgrade of the South Korea network has just been announced. The network is to have 74 high-quality stations, linked in real time to an analysis center. It appears the whole Korean peninsular can be monitored to very low magnitudes.