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A Systems Perspective of Comprehensive Test Ban Treaty Monitoring and Verification

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Abstract

On September 24, 1996, after decades of discussion and more than two years of intensive international negotiations, President Clinton, followed by representatives of (to date) more than 125 other countries, including the other four declared nuclear weapons states, signed the Comprehensive Test Ban Treaty. Each signatory now faces a complex set of technical and political considerations regarding the advisability of joining the treaty. Those considerations vary from country to country, but for many countries one of the key issues is the extent to which the treaty can be verified. In the case of the United States, it is anticipated that treaty verifiability will be an important issue in the U.S. Senate Advice and Consent Hearings. This paper will address treaty verifiability, with an emphasis on the interplay between the various elements of the International monitoring regime, as prescribed in the CTBT Treaty Text and its associated Protocol.¹ These elements, coupled with the National regimes, will serve as an integrated set of overlapping, interlocking measures to support treaty verification. Taken as a whole, they present a formidable challenge to potential testers who wish not to be caught.

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1. Introduction

For the purposes of this paper, a distinction will be made between the terms monitoring and verification. Monitoring will be taken to mean the act of collecting, processing, and reviewing the information used to assess treaty compliance. Verification will be the act of interpreting that data, in conjunction with other considerations, and possibly additional data, to make a judgment regarding treaty compliance. The significance of this distinction is that monitoring is primarily an objective activity involving, for the most part, technical data, and is a major function of the International regime. Verification on the other hand is a more subjective process whose responsibility resides primarily with the National Authorities of the States Parties to the Treaty.

When assessing the verifiability of the treaty, it is necessary to consider the full range of monitoring assets and means available to the National Authorities. This includes those prescribed by the Treaty and its associated Protocol as constituting the International regime and also other means that individual States Parties choose to implement as part of their National regimes. It is also important to understand that verifiability is in the eye of the beholder. Each State Party has a unique set of national security and internal and external political considerations which will determine its standard for adequate verifiability.

2. International Regime

The major elements of the International regime are a) the International Monitoring System (IMS), consisting of networks of seismic, hydroacoustic, infrasound, and radionuclide sensors and an International Data Center (IDC), b) Confidence Building Measures (CBM), c) consultation and clarification, and d) On-site Inspections (OSI). The following sections provide a general description of each of these elements, in order to better appreciate their capability to support verification when utilized as an integrated set.

2.1 International Monitoring System

The IMS is the backbone of the International monitoring regime. It consists of four different types of monitoring networks, a data communications network, and an International Data Center. The four monitoring networks were defined by multinational experts groups with the goal of providing global coverage across a range of potential test environments: seismic for underground, hydroacoustic for underwater, infrasound for atmospheric, and radionuclide for any event which might release radionuclide products into the atmosphere. Data from these networks are transmitted across a communications system to the IDC, which serves as the hub of the network by collecting, processing, distributing, and archiving the data.

Figure 1 - IMS Primary Seismic Network

2.1.1 Seismic Monitoring Network

The primary purpose of the seismic network is to monitor underground tests, but in some circumstances it may also be able to detect tests conducted on or above the earth surface or underwater. As shown in Figure 1, it includes a primary network of 50 seismic stations which provide data to the IDC continuously and in near real time. Many of these primary stations are actually arrays of 9-20 seismometers spaced .5 kilometers (km) to 2km apart in order to enhance the signal relative to the background seismic noise. The primary network is the mechanism by which seismic events will be detected.

Figure 2 - IMS Auxiliary Seismic Network

If events detected by the primary network have characteristics suggesting a need for closer scrutiny, additional seismic data can be requested from an auxiliary network of 120 stations (Figure 2) which provide data only upon request. It is anticipated that data from nearby stations in the auxiliary network, most of which are 3-component stations (as opposed to array

stations), will improve location estimation accuracies and also help distinguish explosions from earthquakes.

Models of these seismic networks estimate that the primary network will have a reasonably uniform detection threshold that corresponds to roughly a 1 kiloton (kt) fully coupled underground nuclear explosion.² The models also predict that by using the combined primary and auxiliary networks, location estimates for underground events will have accuracies on the order of a few hundred to a thousand square kilometers, assuming that the source to receiver paths through which the seismic signals travel are sufficiently well characterized (note that the Treaty text allows requested On-site Inspection areas to be as large as 1000 km²). Characterization of the travel paths will have a significant effect on location accuracy and also on the system's ability to discriminate between explosions and earthquakes.

Average global seismicity rates suggest that there will be on the order of 50 to a few hundred earthquakes per day whose magnitudes are as large as a 1 kt explosion (fully coupled and decoupled respectively). In addition, chemical explosions from mining and excavation work will also produce signals that can be detected by the network. Some of these events can be quickly eliminated from further scrutiny by virtue of their location (e.g., too deep to be a nuclear test or not in an area of interest for a given verifying State Party) or other obvious technical characteristics, but the remainder will require careful application of technical screening criteria and expert judgment. In general, techniques have been developed which are fairly successful at distinguishing between earthquakes and explosions, but they tend to vary from one region to the next and don't work as well at low signal-to-noise ratios. Large, singly detonated chemical explosions present a special challenge because they appear to produce seismic signals which are indistinguishable from those emanating from nuclear explosions.³ Other elements of the International or National Monitoring regimes will be needed to differentiate the two.

Figure 3 - IMS Hydroacoustic Network

2.1.2 Hydroacoustic Monitoring Network

Figure 3 depicts the IMS hydroacoustic network, consisting of six underwater hydrophone stations and five island-based T-phase stations. Explosions in or above the surface of the ocean create hydroacoustic signals which are propagated very efficiently in an oceanic acoustic waveguide called the SOund Fixing and Ranging (SOFAR) channel.⁴ The hydrophone stations are designed to detect these signals directly, while the T-phase stations detect the seismic signal created when the hydroacoustic wave impinges on the island. As such, the hydrophones are much more sensitive (on the order of a factor of 100), but they are also considerably more expensive to deploy (factor of 10).⁵ In the IMS, the more sensitive hydrophone stations will be located mostly in the southern oceans where distances between stations are larger and there is less shipping traffic (hence perhaps better venues for attempted clandestine testing), while the T-phase stations will be located mostly in the northern oceans. Because hydroacoustic signals propagate so well, it is expected that underwater events significantly smaller than 1 kt will be detectable by the IMS hydroacoustic stations. Preliminary research results suggest that for events detectable by three or more stations, and assuming well characterized propagation paths, location accuracies in the broad ocean area should be less than 1000 km².

As with the other sensor networks, one of the key challenges facing the hydroacoustic network is identifying nuclear test events in the presence of competing background events, including undersea earthquakes and ocean-based chemical explosions (military, oil exploration). Certain classes of underwater explosions produce signatures that are readily distinguishable from earthquakes. It does not appear likely however that nuclear explosions will be distinguishable from chemical explosions on the basis of hydroacoustic signatures alone. Other elements of the International Monitoring System may be needed to identify an event remotely.

Figure 4 - IMS Infrasound Network

2.1.3 Infrasound Monitoring Network

The infrasound network is intended to detect the low frequency sound waves generated by an above-ground or, in some cases, below-the-surface nuclear test explosion. These infrasound signals propagate long distances through the atmosphere via a reflection and refraction "waveguide" effect that is somewhat analogous to the SOFAR channel discussed in the hydroacoustic section. Typically, kiloton-size explosions in the atmosphere can be detected at a few thousand kilometers.⁶ As depicted in Figure 4, this network will consist of 60 infrasound stations. A typical infrasound station will include an array of four infrasound sensors (microbarographs) spaced about 1 km apart in a "triangle-and-one" configuration (Figure 5), though the exact configuration will be site dependent. The use of arrays improves the signal-to-noise ratio relative to single sensor configurations and also provides the capability to measure the direction from which the signal comes. The effects of wind noise at each sensor can be reduced by using a set of hoses, each 10-20 meters long, connected to the microbarograph sensing chambers.

Microbarograph With Hoses

Recording/Transmission Site

Typical Array

Figure 5 - Typical IMS Infrasound Station

Discussions in the experts meetings in Geneva, as well as related modeling efforts suggest that the infrasound network will be able to detect explosions in the 1 kt range globally, but the exact thresholds are dependent on atmospheric conditions and thus will vary regionally and

seasonally.⁷ Preliminary estimates of the location capability of the infrasound network operating alone range from about 1000 km² to over 10,000 km², but improved processing algorithms (to get better bearing estimates) and the combined use of infrasound, hydroacoustic, and seismic data should offer improvements.

As is the case with the seismic and hydroacoustic networks, discriminating nuclear explosions from other events will be a key issue. Preliminary research suggests that explosions can generally be differentiated from other classes of events such as thunderstorms, bolides, volcanic eruptions, and sonic booms, but that nuclear explosions and chemical explosions are probably not distinguishable based on infrasound data alone. Other elements of the International or National Monitoring regimes will be needed to differentiate the two.

Figure 6 - IMS Radionuclide Network

2.1.4 Radionuclide Monitoring Network

The purpose of the 80 station IMS Radionuclide network depicted in Figure 6 is to detect the presence of airborne radionuclide products created by a nuclear test explosion. The detection threshold of these systems will be less than 1 kt for above ground explosions. For subsurface detection the threshold will depend on the extent to which venting occurs. While the other detection systems respond on the scale of minutes to tens of minutes, the radionuclide network depends on atmospheric winds to move the debris from the event site to a monitoring station, a process which may require several days. In addition to a delayed response time, this can result in limited location accuracy due to uncertainties regarding wind patterns. An important feature of the radionuclide system is its ability to discriminate between nuclear explosions and other events. It too must deal with competing noise signals (in this case naturally occurring radionuclides and those produced by nuclear reactors, nuclear fuel reprocessing, or medical isotope production and usage), but given adequate signal-to-noise ratios the radionuclide signature can provide strong evidence of a nuclear explosion.⁸

The IMS will include two types of radionuclide sensor systems. All 80 sites will utilize particulate samplers which measure radionuclides transported on airborne particles. At entry into force of the Treaty, 40 of the sites will also include noble gas sensors which measure xenon radionuclides, with the possibility that this number will be expanded to include all 80 sites at a later date. For above ground tests, the particulate radionuclide stations will provide the greatest sensitivity, but for subsurface tests it is possible that only xenon radionuclides will escape into the atmosphere.

Because of the radionuclide network's unique attributes (good detection threshold and identification capability, but relatively slower response time and higher location uncertainties), it is most effective working in conjunction with one or more of the other networks. The challenge will be correlating (in space and time) signals detected by the radionuclide network with events detected and located, but not identified, by the other networks.

Prototype radionuclide stations have been developed which can automatically analyze samples at the stations and forward the results to the IDC. In addition, the Treaty calls for the establishment of certified labs to which samples can be sent for more detailed analysis.

3. International Data Center (IDC)

The IDC is the focal point for collecting, processing, distributing and archiving IMS data. As shown in Figure 7, data from the IMS sensor networks will be forwarded to the IDC either directly or through the National Data Centers (NDCs). Upon receipt, raw data will be verified for authenticity, archived, and made available for distribution to NDCs. In addition, the IDC will routinely process incoming data to produce a set of standard products on behalf of all States Parties. These standard products include integrated lists of all signals detected by the IMS, values and uncertainties of parameters calculated for each event, event bulletins which have been screened according to an agreed-upon set of screening criteria, executive summaries, and customized extracts or subsets of the above as requested by States Parties. In addition, the IDC will provide technical assistance to requesting States Parties in the form of expert technical analysis of data and formulation of requirements for customized selection and screening of data products, and by installing at the IDC algorithms and software provided by States Parties.

Figure 7 - CTBT International Monitoring System

3.1 Confidence Building Measures

In recognition of the special verification challenges posed by large chemical explosions, the Treaty includes voluntary confidence building provisions aimed at decreasing compliance concerns about such explosions. On a voluntary basis, States Parties are encouraged (preferably in advance) to provide notification of and information about any singly detonated chemical explosion in excess of 300 tons.⁹ Also on a voluntary basis, States Parties are encouraged to annually provide information on the location, nature, and frequency of all other chemical explosions in excess of 300 tons. The latter provision would include multiply detonated explosions which are expected to be somewhat less problematic than singly detonated explosions since they tend to produce smaller seismic signatures per weight of explosive and since those signatures sometimes include features not present in nuclear explosions. Also on a voluntary basis, States Parties may invite representatives of the CTBT Organization or other States Parties to visit sites related to the above activities. States Parties are also encouraged to conduct these or other explosions in a manner that will support efforts to better calibrate the propagation of seismic signals in that region.

3.2 Consultation and Clarification

States Parties may avail themselves of the consultation and clarification provisions of the Treaty in order to attempt to resolve possible non-compliance issues without having to invoke an On-site Inspection (though it is done without prejudice to the right of a State Party to request an OSI). Under these provisions, any State Party may request of another State Party, either directly or through the Organization, clarification regarding a matter of possible non-compliance.¹⁰ The clarifying party is obligated to respond within 48 hours and provisions are included in the Treaty regarding approaches for dealing with lack of response or unsatisfactory response.

3.2.1 On-Site Inspections

The Treaty also provides for the possibility of an On-site Inspection to help resolve whether or not a nuclear explosion has taken place in contravention of the treaty. OSI's can be requested by States Parties based on IMS or other data (including open sources and National Technical Means). The OSI is initiated only if at least 30 of the 51 members of the Executive Council (EC) approve within 96 hours of the request. The OSI request can specify an inspection area of up to 1000 km**2 (contiguous with no linear dimension greater than 50 km). The nominal 60 day inspection period consists of a 25 day phase 1 and a 35 day phase 2. During the first phase, inspectors are allowed to use such techniques as visual and photographic inspection (including multispectral and IR), measurements of radioactivity, environmental sampling, and passive seismology (aftershocks). During the second phase, which automatically follows the first unless terminated by a majority vote of the EC (no action by the EC constitutes approval to continue), the inspectors may use additional techniques including active seismology, magnetic and gravitational field mapping, ground penetrating radar, electrical conductivity, and drilling. The inspection team may request a 70-day extension, subject to majority vote approval by the EC.¹¹

4. National Regimes

4.1 National Authorities

Each State Party is obligated to designate or set up a National Authority which will serve as the national focal point for liaison with the Organization and with other States Parties.¹²

4.2 National Data Centers

Annex 1 to the Treaty Protocol lists the IMS stations and identifies the State Party responsible for each station. Many States Parties, including the U.S., are establishing National Data Centers in order to fulfill their responsibilities for implementation, maintenance, and operation of these stations, and to support national processing of data from IMS and national sensors. The U.S. National Data Center is currently being prototyped at the Air Force Technical Application Center (AFTAC).

4.3 National Technical Means (NTM)

The Treaty allows State Parties to utilize "relevant technical information" obtained from NTM data to support requests for OSI.¹³ In addition, State Parties will use NTM to support their own verification judgments. In the case of the U.S., NTM will be used to fill the gap between IMS capabilities and the U.S. monitoring requirements.

4.4 Open Data Sources

The Treaty provides a mechanism by which a State Party may designate as Cooperative National Facilities stations which are not formally included in the list of IMS stations. Once approved and certified by the Organization, these stations can be called upon by the IDC, if

requested by a State Party, for the purposes of facilitating consultation and clarification and the consideration of On-site Inspection requests.¹⁴ In addition, States Parties can utilize other open data sources, including non-IMS type sensors such as commercial imaging.

5. Synergy Between Elements of the Monitoring Regime

By design, the various elements of the International and National monitoring regimes interact synergistically at a number of levels. At the most basic level, the four IMS monitoring networks augment each other by focusing on different potential test environments: underground, underwater, and in the atmosphere. In some cases they also provide overlapping coverage which can improve detection, location, and identification capabilities. One such example is in the oceans where underwater events may produce signals detectable by both the hydroacoustic and seismic networks. Similarly, events at the medium interfaces (air-water, air-land) may produce signals detectable by a combination of all four sensor types. Modelling efforts comparing the detection effectiveness and location accuracy of the integrated system versus each technology subsystem individually for a small, shallow-buried or submerged nuclear explosion show that the integrated system covers significantly more geographic areas and provides significantly better location accuracy (by as much as a factor of 10 in some areas) than can any individual subsystem.¹⁵ Figures 8a and 8b portray this effect qualitatively for a notional small, shallow-buried or submerged event by plotting estimated detection effectiveness (white is better, black is worse) as a function of event location for individual networks and the combined network, respectively.

Figure 8a - Detection Effectiveness for a Small, Shallow-Buried or Submerged Event

Figure 8b - Detection Effectiveness of Combined IMS Network for a Small, Shallow-Buried or Submerged Event

Considering Figures 8a and 8b from a potential evader's perspective reinforces the value of the combined use of the IMS technologies. For the test scenario modelled, geographic areas not well covered by one technology are generally covered by another. Attempts to change the test scenario in order to avoid detection by one technology tend to increase the probability of detection by another. For example, testing deeper in order to avoid detection by infrasound or radionuclide tends to improve the performance of the seismic and hydroacoustic networks and vice versa. Compounding this with IMS performance variability (due for example to changing winds and background noise levels) further increases the challenge to a potential evader.

At a higher level, Treaty provisions for Confidence Building Measures, consultation and clarification, and On-site Inspection offer escalating steps that can be taken to resolve compliance issues. The interaction between OSI and the other elements of the regime is particularly important, since those other elements will be used to make the case for OSI and since they will determine the area to be inspected. It is obvious that the success of an OSI, as well as the need for an OSI, will depend strongly on the accuracy with which ambiguous events can be located.

Finally, the interplay between a State's NTM and the International regime can significantly improve the verifiability of the Treaty. In addition to improving the technical performance of the monitoring system relative to the IMS system alone, NTM has an additional deterrent benefit. This benefit stems from the fact that a potential evader can estimate with some confidence the capabilities and vulnerabilities of the IMS, but is much less able to do so for another State's NTM.

6. Summary

The issue of CTBT verifiability is a complex one driven by a number of technical and political considerations. Taken as a whole the combined set of verification means and measures proposed for the International and National regimes will present a formidable challenge to evaders, but important work remains to be done to ensure that the full potential of this regime is realized. From the U.S. perspective, key elements of the prescribed IMS networks as well as planned upgrades to U.S. NTM must be implemented and research to improve detection, location, and identification capabilities should continue.

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