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**CTBT VERIFICATION RELATED
CASE STUDIES OF
THREE RECENT SEISMIC EVENTS:
NOVAYA ZEMLYA, INDIA AND
PAKISTAN**



DECEMBER 1998

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TABLE OF CONTENTS

PREFACE	iv
ACKNOWLEDGMENTS	v
EXECUTIVE SUMMARY	vi
1. INTRODUCTION	
1A. Purpose and Outline of the Paper	1
1B. The CTBT: What It Is and Is Not	2
1C. The CTBT and Verification: General	4
1D. The CTBT and Verification of the Three Events	5
1E. Implementation of the CTBT Verification Regime	6
1F. Other Sources of Information	8
2. TECHNICAL ASPECTS OF VERIFICATION AND TESTING	
2A. Identifying Explosions	9
2B. The Significance of Measuring the Yield	11
3. NON-SEISMIC METHODS OF VERIFICATION	
3A. Non-Seismic Monitoring Methods Under the CTBT	13
3B. On-site Inspections	14
3C. The Use of Satellite Imagery	14
4. THE THREE EVENTS	
4A. The Novaya Zemlya Event of August 16, 1997	18
4B. The Indian Explosions of May 11 and May 13, 1998	20
4C. The Pakistani Explosions of May 28 and May 30	22
5. IMPLICATIONS OF THE THREE EVENTS FOR CTBT VERIFICATION	
5A. General Implications	23
5B. Specific Implications from the Three Cases	24
5C. India and Pakistan as Test Cases	25
5D. Advance Knowledge	26
6. CONCLUSIONS	28
ANNEX A: LIST OF ACRONYMS AND ABBREVIATIONS	31
ANNEX B: CANADA'S CONTRIBUTION TO THE IMS	33
ANNEX C: YIELD, DETECTION THRESHOLD, AND MILITARY SIGNIFICANCE ...	34
ANNEX D: NON-SEISMIC TECHNOLOGIES IN THE CTBT MONITORING SYSTEM ..	41
REFERENCES	44

PREFACE

On 18 December 1998, Canada deposited its instruments of ratification for the Comprehensive Nuclear-Test-Ban Treaty (CTBT) with the United Nations. Successive Canadian governments for many years have worked diligently toward achieving such an agreement. Constraining the development and qualitative improvement of nuclear weapons as well as the development of new types of nuclear weapons constitutes an effective measure of nuclear disarmament and non-proliferation. As Canada's Foreign Minister, the Honourable Lloyd Axworthy stated:

"The CTBT is an important part of Canada's efforts over the past years to construct an effective international nuclear non-proliferation and disarmament regime. By ratifying, Canada will help to enhance the strength of this regime. I urge all States that have not signed the Treaty to do so immediately and without conditions."

Central to the successful implementation of the CTBT is its verification system. The permanent monitoring systems and other components of the CTBT's verification process constitute a major international undertaking that is commensurate with the importance of this Treaty. The three recent events which constitute the focus of this report provide an important opportunity to gauge in a preliminary way the effectiveness of the nascent and, as yet, incomplete CTBT monitoring systems, particularly the seismic monitoring network. This report concludes that the seismic monitoring network – though still very much in an embryonic form – performed well beyond its design expectations. This provides a strong endorsement for the future ability of the States Party of the CTBT to verify effectively compliance with its obligations. Other conclusions – such as the value of drawing upon non-Treaty sources of data including commercial satellite imagery – are equally significant.

This report is made available as part of the Department of Foreign Affairs and International Trade's policy to share the results of independent research undertaken by the Department's International Security Research and Outreach Program. The views expressed in this report are those of the author and do not necessarily reflect the views of the Department of Foreign Affairs and International Trade or of the Canadian Government.

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EXECUTIVE SUMMARY

The report examines three recent seismic events which can be seen as case studies of the effectiveness of the verification system of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). These events are an incident in August 1997 near the northern Russian island of Novaya Zemlya, and the May 1998 nuclear explosions by India and Pakistan.

By banning nuclear test explosions, the CTBT aims to constrain the development of new nuclear weapons systems and to develop an international norm against nuclear testing. The Treaty was opened for signature in September 1996. The CTBT itself is not yet in force, but its provisional implementing institutions, including the verification system, are being set up in advance. The CTBT verification system consists of global monitoring networks using four technologies: seismic, hydroacoustic, infrasound, and radionuclide; an international data centre to collate and screen the data; and the possibility of on-site inspections to resolve situations where ambiguities about compliance with the Treaty remain.

This paper concludes that the prototype CTBT verification system, notably the seismic monitoring system, although still voluntary and informal in parts and far from complete, did what it was supposed to do in the three cases studied: it detected the events, located them and provided evidence of their nature.

In each case there was controversy or criticism that the CTBT monitoring system did not work, mainly in the context of a US debate about ratification of the Treaty. In the Novaya Zemlya event, some analysts maintained that it could have been a nuclear explosion. The weight of seismological opinion now suggests strongly that it was an earthquake in the Kara Sea, 130 km from the test site. In the case of the Indian and Pakistani blasts, the criticism was that the seismic monitoring system did not detect the low-yield (low energy release) explosions which both countries claimed, and did not see that some explosions were multiple. Also, the system's estimates of yields were much smaller than those announced by the two countries. The critics suggest that low-yield tests of military value could go undetected by the CTBT seismic monitoring system. There was also criticism of the US national satellite observation and analysis capability, which reportedly did not detect preparations for the first Indian tests.

These criticisms attack the CTBT verification system, notably the seismic monitoring system, for failing to do things it was never intended to do. To begin with, although the CTBT bans any test that would result in a release of nuclear energy, it was always recognized that the seismic monitoring system would not be able to detect tests of very low yield. The Indian and Pakistani low-yield tests were below the system's design threshold for detectability. Nonetheless, the system should have been able to see at least some of them. The fact that it did not raises interesting questions, but does not call into question the effectiveness of the CTBT verification system as intended by the Treaty. The same is true of the seismic system's lower yield estimates for the main Indian and Pakistani explosions. Moreover, it is widely believed that a country could not rely solely on low-yield tests to develop advanced new weapons designs, as such designs require full-scale testing in order to be deployed credibly.

With regard to another criticism, separate detection of multiple or simultaneous explosions is not a requirement of the CTBT verification system because a single explosion is enough to constitute a violation of the Treaty.

Satellite observation is not part of the CTBT international monitoring system's mandate, though satellite data may be introduced by any State Party to support a request for an on-site inspection. Neither is the detection of preparations. It was the US national satellite operation that reportedly failed, not the CTBT verification system. Nonetheless satellite observation, and in particular the increasing availability of commercial satellite data, has interesting features that could be of benefit for the CTBT verification regime. The CTBTO should be encouraged to develop expertise in this area.

While the Novaya Zemlya incident was arguably typical of anomalous events that might give rise to a challenge under the CTBT, the Indian and Pakistani explosions were not. The Treaty only applies to States Party, and neither India nor Pakistan have signed, let alone ratified, the CTBT. If they were States Party, they would agree to accept monitoring stations on their territories and to on-site inspections; measures which strongly extend the CTBT verification system's power of detection. Nonetheless, the Indian and Pakistani blasts produced seismic signals that are useful for assessing the CTBT seismic monitoring system.

The findings of this paper suggest that the CTBT verification system should be completed as quickly as possible. Further signatures and ratifications of the Treaty, especially of the United States and Russia, would help to maintain the momentum towards full implementation. The CTBT verification system would benefit technically (as well as politically) by the adherence of holdouts like India and Pakistan, making the monitoring networks more complete and globally effective, and moving towards subjecting all countries to the full legal force – including on-site inspections – of the Treaty.

As the review of the three events showed, there is a great deal of useful data and analysis outside the CTBT verification system, and such data will likely increase in importance. States Party and the CTBTO should be encouraged to develop ways of making optimal use of the information and analysis that will be available outside the formal CTBT verification system, while ensuring that the data used is of the required quality. States Party should promote, both at home and in the CTBTO, a policy of maximum dissemination and availability of data and analysis pertaining to the CTBT verification system, consistent with commitments made to the providers of the information with respect to confidentiality. Individual States Party should consider fostering a community of interested groups with a capability for analysis and interpretation of data pertaining to verification, for instance in universities, scientific institutions and private firms. The CTBTO should be encouraged to develop similar outreach programs.

Canada and other States Party have a strong interest in the technologies used for monitoring nuclear explosions, including satellite imagery, for security reasons but also because of their relevance to large-scale resource and environmental management. The continued development of the relevant technologies and skills should be fostered to support verification.

efforts. The CTBTO should be encouraged to develop a capability for managing satellite imagery, especially with a view to its use in preparing for and carrying out on-site inspections. Both scientific and policy research in support of the CTBT should be fostered.

States Party and the CTBTO should keep under review the various technologies within the current CTBT verification system and outside it, as well as work to ensure that the use of these technologies, and the allocation of resources to them, are optimal in terms of their contribution to the CTBT's goals. The synergies of the CTBT implementing institutions with other non-proliferation, arms control and disarmament initiatives should be examined. Treaty verification is an increasingly important, complex and expensive undertaking. Canada and other States Party should work to ensure that there is effective coordination and cooperation between international verification organizations, that they benefit from each other's experience, that they operate as cost-effectively as possible, and that each State Party gets full value for its contributions and efforts.

**CTBT VERIFICATION RELATED CASE STUDIES
OF THREE RECENT SEISMIC EVENTS:
NOVAYA ZEMLYA, INDIA AND PAKISTAN**

1. INTRODUCTION

1A. Purpose and Outline of the Paper

The purpose of this paper is to review three recent seismic events and to study their implications for the Comprehensive Nuclear-Test-Ban Treaty (CTBT).¹ Each of these events raised questions about the capability of the CTBT verification system to detect and identify similar events. The events studied are:

- 1) the Novaya Zemlya event of August 16, 1997, near a Russian nuclear test site;
- 2) the Indian nuclear explosions of May 11 and May 13, 1998; and
- 3) the Pakistani nuclear explosions of May 28 and May 30, 1998.

The paper's focus is on the verification aspects of the CTBT, as they apply to the three cases, rather than the effectiveness of the Treaty itself. Monitoring and verification will be critical to determining whether nuclear test explosions by States Party, which would violate the treaty, have occurred. The paper does not address issues concerning the scope of the Treaty itself, which are political and can only be addressed by the signatories. For instance, the CTBT verification system has no provisions for monitoring preparations for explosions nor for attempting to prevent them, except by deterring them through the possibility of detection. Any attempt to make the CTBT more pro-active in heading off explosions would require amendments negotiated by the signatories or possibly a new treaty.

In order to see the verification issues in context, some background is necessary. Section 1B outlines what the CTBT does and does not attempt to do. Its objectives and instruments are limited and specific. Verification issues in the CTBT are described briefly in Section 1C and the relation of the three events to the CTBT in Section 1D.

The CTBT has not yet reached the stage of entry into force. The signatories have agreed that the verification system should be fully operational by the time of entry into force and it is being implemented provisionally. In assessing this system, it is important to understand its current status and compare it with what it could achieve when fully operational. Section 1E addresses this topic. Section 1F notes other sources of monitoring information.

¹ Canada signed the CTBT on 24 September 1996 and deposited its instruments of ratification with the UN on 18 December 1998.

Section 2 provides background on technical aspects of seismic monitoring and on how explosions are distinguished from earthquakes. Seismic monitoring is the technique most useful for detecting, locating and identifying underground explosions, and was the key method in the three cases discussed in this paper. Section 2B discusses briefly the significance of the yield or energy release of an explosion. Annex C describes how the yield is calculated, discusses the lower limits of yield that can be detected and identified, and outlines the military significance of explosions with yields below this threshold of detection.

Non-seismic methods for verifying explosions are outlined briefly in Section 3, including the utility of satellite observations. Annex D provides some technical details on the radionuclide, hydroacoustic and infrasound networks. Section 4 discusses the three events, which are the central focus of this report, along with the results of verification efforts by the provisional CTBT organization and by other groups. Section 5 assesses the CTBT seismic monitoring system in light of what should be expected of it and how it performed in these three cases. Conclusions and recommendations follow in Section 6.

1B. The CTBT: What It Is and Is Not

The CTBT, under discussion or negotiation on and off for almost 40 years, is seen by many observers as a major step forward in nuclear arms control. Canada played a lead role in the negotiation of the CTBT and continues to be a strong proponent of the Treaty.

Under the CTBT, a State Party undertakes:

- not to carry out any nuclear weapon test explosion or any other nuclear explosion, recognizing that this undertaking will constrain the development and qualitative improvement of nuclear weapons and end the development of advanced new types of nuclear weapons;
- to prohibit and prevent any such nuclear explosions at any place under its jurisdiction or control; and
- to refrain from causing, encouraging or in any way participating in the carrying out of such explosions.

The CTBT does not prohibit the possession or even the production of nuclear weapons. Nor does it ban the development of new weapons designs, or even their testing, as long as nuclear explosions are not involved. Nor does it ban the maintenance of infrastructure, such as test sites, that could be used for nuclear explosions. The Treaty must be seen in the broad context of other instruments of non-proliferation, arms control and disarmament (NACD), notably the Nuclear Non-Proliferation Treaty (NPT). Under the NPT, non-nuclear weapon States Party (NNWS) agree not to possess, manufacture or acquire, or to help others acquire, nuclear weapons. This is a much stronger obligation and would, if observed, limit the development of a nuclear weapon capability at an early stage.

The main burden of the CTBT's constraints fall on a limited number of states, notably the five states who are declared nuclear weapon states (NWS) under the NPT and any so-called "threshold" state (i.e. one believed to possess nuclear weapons or the capability to develop them rapidly) party to the CTBT but not the NPT. Of the threshold states, India and Pakistan have signed neither the NPT nor the CTBT. North Korea, considered by some as a threshold state, has signed and ratified the NPT but has not signed the CTBT. Israel has signed the CTBT but not the NPT and appears to be the only threshold state that would be constrained by the CTBT at this time.

There is always the risk that some parties to the NPT will violate that Treaty by developing weapons clandestinely, as Iraq tried to do. The CTBT would help to ensure that they could not test the weapons without being caught.

In its specific function, the CTBT has a limited but important role: it helps to put a cap on technological arms races by freezing the designs of new nuclear weapons by States Party, especially designs of compact fission-boosted and two-stage thermonuclear weapons, and of miniaturized low-yield tactical weapons. These are the weapons that a modern arsenal using missiles would require. The CTBT constrains the NWS and the threshold states alike. In principle, the NWS could use methods other than nuclear test explosions to develop new designs, such as computer codes combined with testing of individual components and hydrodynamic experiments that release no nuclear energy. However, it is believed that most advanced weapons designs would need full-scale testing to ensure operational confidence levels. Certainly, the CTBT obligations make development of new nuclear weapons more problematic.

The CTBT, however, will not prevent the development of weapons that do not require testing, such as fission gun-type weapons or even, in some cases, first-generation fission implosion weapons.

More broadly, the CTBT is helping to establish a global norm against nuclear testing. It remains to be seen whether the Indian and Pakistani explosions are a last gasp for nuclear tests or the beginning of a new and threatening tendency to embrace them.

The monitoring and verification of the CTBT is a *post hoc* exercise. The CTBT is not pro-active. It does not prohibit preparations for testing, nor does it seek to prevent tests directly by actions based on advance knowledge. For some states, national technical means (NTM), such as satellites and other intelligence gathering systems, are available to provide advance notice. If preparations are detected by such means, countries can take preventive action as they see fit. The CTBT itself seeks to detect violations only when they occur or shortly afterwards. Of course, it is hoped that the possibility of detection of tests will serve as a deterrent, because of the consequences that would ensue; but verification comes after the event. Only when an anomalous event has occurred can possible non-compliance with CTBT obligations be verified.

As with any treaty, the CTBT applies only to States Party. Its verification system is aimed at detecting States Party who cheat on their obligation not to test. It assumes that the

possibility of detection will be a deterrent to violation of the CTBT. Except for helping to establish a norm against testing, the CTBT does not address the situation of countries who are not signatories or parties to it, and who want to test openly as a way of sending a political message. That was the situation of India and Pakistan in May 1998.

1C. The CTBT and Verification: General

Verification was a basic concern in the negotiations leading to the CTBT and is still a subject of some controversy. Countries that agree to forego nuclear testing will want strong assurances that others are doing likewise, so monitoring and verifying is essential. Lack of confidence in the ability of international monitoring systems to detect and identify nuclear explosions was a key reason for failure to negotiate a CTBT in 1963 and again in the early 1980s.

In retrospect, it is arguable that a CTBT in 1963, based on the verification technologies available at the time, primarily seismic, could have been effective, and would have done much to curb the extensive nuclear testing that occurred in the 1960s, 1970s and 1980s.²

The CTBT was finally negotiated in the Conference on Disarmament in Geneva during the years 1994-96. It was adopted by the United Nations General Assembly on September 10, 1996 and opened for signature at the UN in New York later that month. Improved confidence in seismic and other remote monitoring technologies, and the agreement of the major weapons states to further improve monitoring through in-country networks and on-site inspections, were important factors in reaching broad agreement on the CTBT.

As of December 1, 1998, the CTBT has been signed by 151 countries and ratified by 21. Ratification by a designated list of 44 countries – those with nuclear facilities – is required before the CTBT enters into force. Ten designated states have ratified, including the UK and France among the NWS. The United States and Russia have not yet ratified. Three designated states have not signed: India, Pakistan and North Korea. India had previously said it would not sign and Pakistan had said it would not sign if India did not sign. These positions have evolved since the explosions of May 1998. Prime Minister Atal Behari Vajpayee of India told the United Nations General Assembly on September 23, 1998 that India hoped to bring negotiations on adhering to the CTBT to a conclusion by September 1999. The following day, Prime Minister Nawaz Sharif of Pakistan told the Assembly that Pakistan was prepared to adhere to the CTBT before September 1999, in conditions free from coercion or pressure. The signature of both countries now appears more promising but meeting their conditions will continue to be a challenge. North Korea has not indicated any intention of signing the CTBT.

²

Richards and Zavales, 1996

In the United States, President Clinton and the US Administration are supportive of the CTBT. However, there is some opposition to the CTBT in the US Senate and elsewhere in the US. Continuing concern about verification is one of the main reasons cited for this opposition.³

1D. The CTBT and the Three Events

Each of the three events studied in this paper raised questions about the capability of the international monitoring system – particularly the seismic network – to detect and identify nuclear explosions. The event at Novaya Zemlya was arguably typical of the type of event that might give rise to a challenge under the CTBT. In that case, several agencies of the US government initially indicated that the event could have been a nuclear explosion at a main Russian test site, although seismic data suggested strongly that it was an earthquake located under the ocean, at a distance of 130 kilometers from the test site. It was important to identify this event because a nuclear test explosion by Russia would have violated its commitment as a CTBT signatory.

In the cases of the Indian and Pakistani explosions, the CTBT monitoring system correctly detected, located and provided evidence for the identification of the main test explosions. These main tests had yields above one kilotonne, the threshold yield level for which the system was designed.

Critics were concerned that the low-yield tests below one kilotonne, claimed by both India and Pakistan, were not detected by the international networks.⁴ Also, India and Pakistan both carried out several tests simultaneously and it was not clear that the separate tests could be detected. Finally, the yields estimated by observers were smaller for both countries than the yields they announced.

It is important to note that the Indian and Pakistani explosions were not representative of the kind of event that the Treaty would be expected to address. The results achieved by the CTBT monitoring system respecting these two cases should not be taken as fully representative of what that system could achieve in its eventual form and field of application, for reasons outlined further below.

As India and Pakistan are not signatories to the CTBT, it does not apply to them and would not even if it were in force. They have no obligation to provide monitoring stations on their territory nor are they subject to on-site inspections. They have no legal constraint on testing or developing nuclear weapons. Far from hiding their tests, they both boldly proclaimed their

³ Helms, 1998

⁴ The yield of an explosion is the amount of energy released, measured in tonnes or kilotonnes (kt) of chemical high explosive equivalent. Low-yield nuclear explosions are called sub-kilotonne or sub-kt explosions if they release less than a kilotonne of chemical high explosive equivalent.

success. Some observers have suggested that they may even have exaggerated the size and number of explosions, for political purposes.

It should be kept in mind that the CTBT was agreed with the full knowledge that there would be a threshold yield below which the seismic monitoring system would not be able to detect and identify events with certainty. The design threshold was about 1 kilotonne for a well-coupled blast. Events of lower yield can be detected if there are good signals available from regional seismic stations. Detection of simultaneous explosions is not essential for the immediate purposes of the CTBT because a single nuclear explosion by a State Party would constitute a violation of the Treaty.

In the Indian and Pakistani cases, the implicit challenge to the CTBT monitoring system, as expressed by critics of the CTBT, was not so much to detect and identify a clandestine event, but rather to detect announced low-yield explosions at a level well below that for which the CTBT monitoring system was designed, and to discern whether multiple, simultaneous explosions had indeed occurred as claimed. The failure to detect the low-yield explosions gave rise to claims by some that compliance with the CTBT could not be verified.

Satellite observation is not part of the CTBT monitoring system, although States Party can use information from satellite imagery or from other "NTM" (national technical means)⁵ to support or oppose requests for on-site inspections. The reported failure by the US to detect preparations for the first Indian test was a failure of American NTM, not of the CTBT monitoring mechanisms. However, it has some implications for the overall monitoring system.

1E. Implementation of the CTBT Verification System

Notwithstanding the uncertainty about the date of the entry into force of the CTBT, signatories have agreed that the organization and facilities required for its implementation should be operational by that date. Thus the signatories are establishing, in Vienna, the Provisional Technical Secretariat (PTS) of the CTBT Organization (CTBTO), which is carrying out until entry into force the administration of the Treaty and establishing the monitoring systems that are such an important part of it.

The PTS began work in March 1997, along with other components of the CTBTO: the International Monitoring System (IMS), which will gather data from its networks of monitoring stations, and the International Data Centre (IDC), which will collate and analyze the data from the IMS according to defined procedures.

Products from the IDC will be provided to States Party, and shall be "without prejudice to final judgements with regard to the nature of any event, which shall remain the responsibility

⁵ NTM includes monitoring networks, electronic intercepts, etc.

of States Party".⁶ Thus it is up to the States Party, individually and collectively, to determine whether a nuclear test explosion has taken place and to decide on further measures, if any.

The IMS is a set of networks based on four monitoring technologies: seismic, infrasound, hydroacoustic, and radionuclides. The IMS will consist of 50 primary and 120 auxiliary seismic stations, 60 infrasound stations, 11 hydroacoustic stations, and 80 radionuclide stations. All the latter will sample particulates. It is planned that at entry into force, only half will sample noble gases, but when the network is finalized all radionuclide stations will do so.

The primary seismic stations will transmit data to the IDC continuously and automatically. The auxiliary stations will provide data on request. The networks are drawn in part from national facilities of the States Party, but many of the stations are being built expressly for the IMS.

As of May 1998, well over half the IMS seismic network stations were operating, but not all of these are certified yet as providing data of the quality required by the CTBT. Some of the stations are new and not yet fully proven. Others are due for upgrades. For the other monitoring networks, fewer than half the stations were operating. Thus the IMS network is operational but still some distance from its planned final capability.⁷ Canada's contribution to the IMS is outlined in Annex B.

If an event detected on the territory of a State Party by the IMS or other means is considered suspicious, other States Party can request an on-site inspection on the territory of that State. Data from non-IMS sources can be used to support or oppose the request. On-site inspections are expected to provide definitive proof of whether or not a nuclear explosion has occurred. They are limited to an area of 1 000 square kilometres of territory. One overflight by aircraft is permitted. Subsequent overflights can be carried out with the permission of the inspected State Party.

A prototype International Data Centre (pIDC) was set up in Arlington, Virginia and funded by the US Department of Defense. It has been working since January 1995, demonstrating some of the operational requirements of an eventual IDC, establishing a cooperative international infrastructure for verification of the CTBT, and helping to develop and transfer the relevant software, methods and technologies to the IDC. When the IDC is established, some staff members may relocate to Vienna, but there is no intention of transferring the pIDC *per se*.

The pIDC has no formal relation with the CTBT. Nevertheless, it is gathering data, on a voluntary basis, from both IMS and non-IMS stations, developing screening criteria, carrying out

⁶ Article 18 of Part I of the Protocol to the CTBT.

⁷ For various accounts of its status see van Moyland and Clark, 1998; Sykes, 1997; and MacKenzie, 1997.

analyses of recorded events, and producing event report bulletins in the way that the IDC is expected to do. References in this paper to the output of the CTBT monitoring system in the three cases studied are in reality references to the output of the pIDC, which is informal, voluntary and incomplete. The pIDC thus serves as a proxy for the eventual IDC which is expected to continue and expand the current capabilities of the pIDC.

In this paper we will refer to the CTBT “monitoring system” as the four networks of the IMS plus the data processing function of the pIDC or the IDC. The seismic monitoring network is the key one of these for underground explosions and was the most important source of information in the three cases studied. The “verification system” of the CTBT will be taken to mean the monitoring system plus on-site inspections, confidence building measures and other actions taken in the context of the Treaty, including interpretation of IDC data by States Party. The broader term, CTBT “verification regime”, includes the CTBT verification system, but also comprises the use and analysis of data from other sources such as national technical means and non-government bodies.

Many NACD initiatives have separate implementing organizations, like the CTBTO, and often matching separate national authorities as well. It is important to work to ensure that these entities cooperate effectively and coordinate their activities in areas of common interest such as sharing of experience, training, principles and procedures, logistics, etc.⁸

1F. Other Sources of Information

During the preparation of this paper, it was striking to observe the extent of the availability of independent monitoring information about nuclear testing. While the IMS will be a reasonably comprehensive monitoring network, with 180 seismic stations, there are, in fact, some 10,000 seismic stations operating around the world.⁹ Many are run by government agencies and form part of national networks, like Canada's. Others are in the hands of universities, independent institutes, private firms or NGOs. Some of these form part of national or international networks. Much of the publicly available information about the three events studied here comes from these independent sources, who in many cases have Internet websites.

An example is the Incorporated Research Institutions in Seismology (IRIS), a university consortium involving some 90 universities that operates a global network for earth studies. Another example is the amount of commercial satellite imagery which is now available from a range of sources, and which can play a role in monitoring nuclear explosions. High resolution (one metre or less) satellite imagery is expected to be commercially available within a few years.

⁸ Crawford, 1997.

⁹ Richards and Kim, 1997.

2. TECHNICAL ASPECTS OF VERIFICATION AND TESTING

2A. Identifying Explosions

The goals in verification under the CTBT are to:

- 1) Detect an event;
- 2) Locate the event within a few tens of kilometres, or better; and
- 3) Identify or characterize the source of the event, (e.g. earthquake, rockburst, explosion).

As noted, actual judgements about the nature of events are the responsibility of the States Party, not the CTBTO.

Under the Limited Test Ban Treaty of 1963, nuclear explosions in the atmosphere, outer space and under water are prohibited. The possibility of their detection in most cases, using national technical means, made the Limited Test Ban Treaty possible. For underground testing, seismic methods are the best for the goals of verification listed above. This section of the paper focusses on seismic monitoring.

Earth movements and vibrations from earthquakes have long been studied by increasingly sensitive seismic stations around the world. An added stimulus to seismic studies since the 1960s has been the desire to detect nuclear explosions and to distinguish them from earthquakes, rockbursts in mines, and chemical explosions, which the seismic stations will also record.

Seismic disturbances propagate vibrations through the earth which can be detected by sensors as continuous signals recorded as amplitude versus time. The vibrations propagate as body waves into the earth, from whence they return to the surface at large (teleseismic) distances, beyond 2000 kilometres. They also propagate along the earth's surface and within its thin crust, as surface or regional waves. The period of the vibrations of interest varies from less than one second to about 20 seconds, and in some cases much more. At a given station, a variety of different waves may or may not be present from a particular seismic event.¹⁰

The nature of the seismic signal depends on the geologic medium in which the event occurs, the continental crust material through which some of the waves travel, and the geologic medium immediately below the sensor. Corrections can be made for these geologic differences. Thus a previous history of calibration of seismic events from a given source at a given receiver station provides very valuable information.

¹⁰ Chun, 1991; Richards and Zavales, 1996.

The signal of a nuclear explosion can also vary with measures taken to evade detection, such as setting off an explosion in a large cavity or in loose, unconsolidated material. Both these approaches tend to decouple the blast energy, so that less of it goes into seismic vibrations.

Detection simply requires a signal that is distinguished from the seismic and instrumental noise in the recorded seismogram. The relative travel times of different waves to different receivers can usually localize the event to within a few tens of kilometres, with considerable variation in precision depending on background noise, source/receiver geometry and calibration of the area. Detection by a number of stations can improve the precision of the location, especially if they are within about a thousand kilometres of the explosion.

Chemical and nuclear explosions are very difficult to distinguish using seismic information alone. Accordingly, the CTBT includes provisions in Article IV E for voluntary exchanges of information about chemical explosions to help in verification efforts.

Because earthquakes are so numerous and so unpredictable in their timing, distinguishing nuclear explosions from earthquakes is one of the main challenges of the CTBT verification regime. Fortunately, earthquakes and explosions differ in a number of ways that can be used to differentiate them. Methods of distinguishing earthquakes from explosions include the following:

- 1) Many earthquakes occur at greater depth than would be feasible for explosions.
- 2) Earthquakes tend to occur more often beneath the oceans. Explosions within the body of the ocean or on the seabed are easily detected and identified by hydrophones. An ocean location is generally taken as an indicator of an earthquake rather than an explosion.
- 3) Earthquakes tend to occur much more frequently near certain fracture zones in the earth's surface, such as rift valleys or subduction zones. Seismic events in areas where there are few naturally occurring earthquakes may attract attention from CTBT verifiers.
- 4) Most nuclear explosions have occurred at known nuclear testing sites, so the locations are known. Preparations for testing are observable by satellite, so even a new site might be located and observed well before any testing occurs. Seismic events in heavily populated areas are more likely to be earthquakes.
- 5) Explosions have a spherical outward compression wave, whereas earthquakes are the result of shear motion, which radiates shear and compression waves

differently, according to their direction relative to the direction of the shear.¹¹ This means that the first motion recorded from an explosion is almost always up, whereas the first motion of an earthquake may be up or down. First motion has not proved to be a decisive indicator.

- 6) Earthquakes are richer in surface waves, relative to body waves, when compared to explosions of the same magnitude.
- 7) Earthquakes are richer in shear body waves, relative to the compression body waves, when compared to explosions of the same magnitude.
- 8) Explosions tend to be more impulsive and to have more energy at higher vibration frequencies.

Using these and other discriminants, analysts can usually distinguish between earthquakes and explosions if an event is recorded at several stations with a good signal to noise ratio.

2B. The Significance of Measuring the Yield

The goal of the CTBT verification system is to detect, locate and identify nuclear explosions, regardless of the yield. However, knowledge of the yield can be useful in a number of ways. First, it may be a useful indicator of the kind(s) of explosion(s) that may have taken place. For instance, two-stage thermonuclear devices are not likely to have yields less than 10 - 15 kt¹² and boosted fission devices are not likely to have yields less than 1 kt.¹³ Second, blasts where more than a few hundred tonnes of chemical high explosives are detonated in a single explosion are rare (as opposed to ripple-fired blasts, common in open-pit mining, which are discussed elsewhere) and would likely have unique explanations.

Third, it is very important to know the lower limits of yield that can be detected in particular circumstances, because of the implications for clandestine testing. The CTBT is a zero threshold treaty; it bans all nuclear explosions, regardless of how small. While the term "nuclear explosion" was left undefined in the CTBT, it is understood to mean any test activity resulting in a prompt release of fission or fusion energy. In turn, this means that no prompt fission chain reaction with a non-zero yield is allowed. (A chain reaction that just barely sustains itself but produces no net energy is possible, but difficult to achieve in practice under explosive conditions.)

¹¹ A compression wave alternately compresses and expands the medium in which it travels. Sound waves are compressional. A shear wave moves the medium transversely to the wave motion. Surface water waves or waves propagated along a rope are shear.

¹² Wallace, 1998.

¹³ Coalition, 1998.

However, there is a lower limit to the ability of the IMS seismic monitoring system to confidently detect and identify nuclear explosions. As noted above, this threshold is in the range of one kilotonne for well-coupled blasts, or lower if there are good regional stations available. Thus, there is a range of explosions which are forbidden by the Treaty but which cannot be reliably detected by the IMS seismic network and could therefore escape its purview.

This detection gap was known and understood when the CTBT was negotiated. The signatories clearly believed that they would be better off with a treaty that has such a gap than with no treaty at all. A threshold treaty was considered but rejected, as it could involve a lot of contentious discussion about whether yield thresholds had been violated.

The gap between what the CTBT prohibits (i.e. all nuclear explosions) and what it can detect and identify (i.e. well-coupled explosions above about a kilotonne) focusses attention on the military significance of tests with yields that fall in this sub-kt gap. If testing of military significance can be carried out below the threshold of detection, it could allow countries who violate their CTBT commitments to develop nuclear weapons without being detected seismically. It should be kept in mind that even if events are not detected seismically, there are other means such as the other IMS networks, or NTM, that could arouse suspicions, and possibly lead to an on-site inspection.

The ability to detect and identify events at very low yields would minimize the range of the undetected blasts, extend the range of blasts covered by the verification system and make the CTBT more effective. Thus, the ability to determine yield accurately helps to build confidence in the CTBT.

The yield of an explosion is determined by its magnitude. The magnitude of a seismic event is measured as the amplitude of the vibration, corrected for distance and geologic media. The magnitude generally used is "mb", that of the compressional body wave. The magnitude is proportional to the log of the yield. An mb of 4 corresponds to a yield of about 1 kilotonne for a well-coupled blast. This is the generally accepted detection goal of the CTBT seismic monitoring system.

If a number of good quality regional stations are available within a thousand kilometres of the source, well-coupled events with yields down to a few hundred tonnes can be detected and probably identified, especially if there is a recorded history of seismic events, ideally both earthquakes and explosions, in the area of the source.

Annex C provides further background on the measurement of yield, the threshold yields for detection in different situations and the military significance of tests that could be carried out below the threshold for detection.

With respect to military implications of testing below the detection threshold, it seems unlikely, on balance, that a State Party to the CTBT would attempt to develop full scale deployable weapons by relying on testing in the sub-kt range. It would run the risk of detection

by other means, and it does not appear that a credible operational capability for a new weapon could be confidently attained by testing in that range. As noted in Section 1B, the possibility of detection is not a deterrent for a non-signatory country that wants to test openly.

One source¹⁴ suggests that the greatest utility of sub-kt testing would accrue to potential proliferators trying to improve the yield of primitive fission weapons, without boosting. Such weapons are no longer part of the arsenal of the US. Another source¹⁵ states that hydronuclear tests have no military value, either for weapons states to develop new weapons designs, or for non-weapons states to develop an initial capability.

Also it is clear that potential proliferators could confidently build gun-type and, with less confidence, implosion-type, fission weapons, without any need for testing. This would violate their NPT commitments, if they are Party, but not their commitments under the CTBT. Thus, the benefits of clandestine sub-kt testing for States Party, given the risks of detection, would appear to be fairly marginal. But that is no guarantee that such tests could not occur.

3. NON-SEISMIC METHODS OF VERIFICATION

3A. Non-Seismic Monitoring Methods Under the CTBT

The three non-seismic technologies used for monitoring under the CTBT (radionuclide, hydroacoustic, and infrasound) are all primarily aimed at detecting nuclear test explosions in the atmosphere or under water. Such tests are already prohibited by the Limited Test Ban Treaty of 1963, and are seen as less likely than underground tests. Nonetheless, it is important to have monitoring systems in place to ensure that the atmosphere and the oceans remain off-limits, as the CTBT bans all nuclear explosions anywhere. Also, radiological and other consequences of testing in the atmosphere and the oceans are more serious than for underground testing. The three technologies can also help to detect explosions which are set off close to the surface of the ground or the water, or under the seabed, if energy or radioactivity is coupled into their medium of primary focus. The hydroacoustic network will pick up earthquakes under the seabed.

Given the difficulties and uncertainties inherent in detecting low-yield nuclear explosions, the CTBT verification regime is likely to need all the help it can get, and a diversity of technologies that complement each other is desirable, in order to exploit synergies and render evasion more difficult. It would seem sensible to complete and develop the three non-seismic networks, to extract and analyze whatever information can be obtained from them, and to gain experience with them. At the same time, it will be important to direct the verification regime's scarce resources where they are most useful. This will mean keeping the effectiveness of the different technologies and the relative resources allocated to them under continuous review.

¹⁴ Cochran and Paine (1995).

¹⁵ Garwin (1997).

Although the non-seismic technologies used by the CTBT monitoring system did not play an important role in the three events studied in this paper, they will be important components of the eventual monitoring system, and could make key contributions to verification. Annex D outlines these three technologies in more detail.

3B. On-site Inspections

If a State Party to the CTBT has concerns about non-compliance by another State Party, its first recourse is to consult and attempt to clarify the matter. If the matter is still unresolved, the State Party can request an on-site inspection.

On-site inspection was a controversial issue in the negotiating of the CTBT.¹⁶ Details of the process take up almost half the CTBT and its Protocol. The Executive Council of the CTBT, a group of 51 States Party, must decide whether or not to approve the inspection within four days of the receipt of a request. In making the decision, the Council would look at the evidence presented by the requesting State Party, including both IMS and non-IMS data. The latter could include satellite imagery or other information.

An on-site inspection would be a major undertaking and would be quite intrusive, although procedures are specified by the detailed Protocol negotiated as part of the CTBT. A team of up to 40 people could be involved for several months. It would require both extensive planning and rapid execution, as much of the evidence could disappear quickly (e.g., radioisotopes with short half-lives and aftershocks from relaxation and collapse of the cavity are short-lived). The area targeted is limited to 1,000 square kilometers, so accurate prior location would be important. Satellite photography and other baseline information would be valuable in the planning phase, in order to make the best use of limited time and resources during the actual inspection.

The inspection team has the right to one aircraft overflight. Further flights must be approved by the host country. The inspection could use of a variety of technologies, including drilling, geochemical sampling, geophysical probing, radionuclide measurement, photography, and aerial remote sensing.

All in all, an on-site inspection is expected to provide definite proof as to whether a nuclear test explosion took place, and a fair amount of information about its nature, yield, etc., as well as about the identity of the violator.

3C. The Use of Satellite Imagery

Satellite imagery is becoming one of the most effective mechanisms for international non-proliferation and arms control verification, although, of course, it is also used for specific

¹⁶ Cole, 1995.

national security purposes. Until recently, the development and use of high-resolution satellite imagery has been largely in the hands of national agencies, because of military or resource management reasons. Nonetheless, it has become an accepted method of intelligence gathering, and many countries recognize the benefit of not interfering with the gathering of satellite intelligence by other countries.

In the last few years, high resolution satellite imagery has become available on a commercial basis. France made imagery with 10-metre resolution available in 1986. Russia began to supply selective 2-metre resolution images in 1991, by optically degrading its original data. India launched a satellite with 6-metre resolution in the early 1990s. In the face of this increasing commercial competition, the US authorized the commercial sale of 1-metre resolution imagery in 1994. The US has licensed four companies to provide such imagery, and they are expected to begin operations over the next few years. The new generation of satellites and sensors should provide imagery in near real time.¹⁷ As a measure of how quickly this field is developing, Microsoft recently began offering Russian satellite imagery with 2-metre resolution over the Internet, in conjunction with Carterra and Russian interests. The price is in the range of \$25 per image, at least 40 times cheaper than has been available till now.

In the years leading up to the agreement on the CTBT, it seemed that satellite imagery could be one of the technologies used to monitor compliance with the Treaty. For a number of reasons, this did not materialize. One obstacle was that most of the high quality data, along with the skills to process and analyze the large amounts of information involved, remained with national agencies, in most cases linked to national security interests. They tended to guard closely their data and the means for gathering it, while being prepared to make the results available under certain circumstances. They did not want to become arbiters, on the basis of their data and interpretation, of international disputes. Similarly, other countries did not want to depend on data provided by only a few advanced countries.

The possibility of having the CTBTO put up its own system was estimated to be prohibitively expensive. A remote-sensing satellite can cost \$500 million and the launching another \$100 million.¹⁸ Ground stations and analytical capability will add to the cost. Thus commercial imagery might be a much cheaper option. Images covering a few tens of kilometres on each side will cost a few thousand dollars each (although, internet dissemination may lower the cost considerably). This is cheap, if the area to be monitored is small and its location known. However, the total cost can add up if large areas are monitored on a continuing basis. At the time of negotiation of the CTBT, commercial imagery did not appear to offer a viable and cost-effective alternative, although it is making very rapid progress.

A system dedicated to monitoring for an international treaty would have to observe strict protocols regarding equal treatment of States Party. Thus it may need to spend a lot of time and

¹⁷ Baines, 1997; Gupta and Pabian, 1998.

¹⁸ Baines, 1997.

effort monitoring areas that are of minor interest in terms of real verification. National systems, on the other hand, are free to direct their sensors to areas of prime interest. Commercial systems are likely to become increasingly responsive to the desires of customers to get the imagery they want, when they want it.

The CTBT is intended to verify compliance, not to anticipate violation. Preparations for tests are not forbidden by the CTBT, although they are by the NPT. The CTBT has no mandate for verifying such preparations, and so satellite capability in this area would not be directly relevant to its existing objectives. As noted earlier, any move toward making the CTBT verification regime more pro-active in detecting preparations for tests would require amendments to the Treaty, or a new treaty.

The CTBT monitoring mechanisms are intended to check for violations after the event, and to follow up on evidence that might indicate a nuclear test explosion had taken place. In seeking or opposing an on-site inspection, States Party are free to bring whatever evidence they choose, whether gathered by the IMS or not. In particular they are free to bring evidence based on satellite data from their own national systems, from those of other countries, or from commercial imagery.

The recent and continuing progress in the availability of high resolution commercial imagery from a range of sources suggests that it could play an increasing role in the verification of agreements such as the CTBT. A good level of coverage can be obtained for millions of dollars rather than the billions involved in putting up satellites and setting up ground stations. While some imagery might still be restricted in special cases by national governments, it is expected that commercial imagery will generally be broadly available from a variety of sources. Private groups and individuals have already used commercial imagery to predict, and rapidly report on, test explosions by several weapons states.¹⁹

Satellite imagery can be used to show whether test preparations have taken place or, after an alleged explosion, to locate the crater and other evidence that the explosion did indeed occur. One source²⁰ reports on such an analysis in 1996 on the Indian test site, using available commercial imagery, including French SPOT imagery at 10 metres, Russian KVR-1000 imagery at 4 metres, and Canadian Radarsat imagery at about 6 metres. The authors showed that recent changes and signs of activity at the test site were consistent with preparations for a nuclear test. They also located the subsidence crater from the 1974 explosion, which had been reported to be in several different places within a 30 km radius.

The US detected similar preparations late in 1995 and put pressure on the Indian government to cease its testing. The Indian government of the day agreed. (Interestingly, Mr. Vajpayee took power briefly in 1996 and put into action his party's declared position of

¹⁹ Gupta and Pabian, 1998; Gupta and McNab, 1993

²⁰ Gupta and Pabian, 1996

favouring Indian nuclear testing, but his government fell before it could accomplish any testing. When he returned to power in 1998, he moved quickly to carry out the tests.)

Commercial imagery could be used under the CTBT to support or oppose a request for an on-site inspection. When on-site inspections do take place, satellite imagery could be very useful in guiding and focussing the resources of the investigation, especially the scarce overflight time available.²¹

The IAEA safeguards system, set up to monitor compliance with the NPT, has an increasingly anticipatory role in detecting non-compliance with that Treaty. The powers of the IAEA are being extended to look for and monitor clandestine nuclear facilities, not just those already subject to its safeguards. The use of satellite imagery in such an anticipatory capacity will probably develop most intensely in that agency over the next few years. Its use there will bear watching.

It could be useful for the CTBTO to develop a capability for managing satellite imagery, especially for on-site inspections, though this should be balanced against the requirement it faces to get the IMS and IDC running and the recognition that satellite imagery is not part of its mandate. Given the advances in this area, it will be important for the CTBT signatories to keep it under review. It would also be useful for countries like Canada to develop further their national capacities in satellite imagery. At the very least, they would want to see, on their own territories, what others are able to see. With its vast geographic extent, Canada has a well-developed expertise in the use of satellite imagery for resource management purposes, and a continuing interest in being a world leader in this area. The Canadian Centre for Remote Sensing in Natural Resources Canada and the Canadian Space Agency are world leaders in some areas, such as radar imaging. Canada should encourage the development and application of skills and technology in the use of commercially available imagery for national and international security purposes, including the use of imagery for verification purposes in treaties such as the CTBT. As with seismic detection and the other IMS technologies, excellence in satellite imagery would ensure that Canada makes an effective contribution to the CTBT, maintains a leadership role in emerging technologies, and benefits from the commercial opportunities that may arise.

Clearly the world is becoming more transparent. Detailed satellite information will be available to anyone who can pay a few thousand dollars for an image and develop the skills required for interpretation. International organizations and national governments concerned with verification will have to keep up or be overtaken by events. The widespread availability of seismic information, and its use by a variety of actors, could be an indicator of where we may be going with satellite imagery, which is likely to be even more widely used.

²¹ Cleminson, 1997.

4. THE THREE EVENTS

4A. *The Novaya Zemlya Event of August 16, 1997*

On August 16, 1997, a seismic event was detected near Novaya Zemlya, a large island in the Kara Sea off the Arctic coast of Russia. Previous nuclear test explosions have occurred on sites within two large areas on Novaya Zemlya. The event is interesting in that seismologists quickly agreed that the event was an earthquake beneath the Kara Sea, at a location about 130 km from the suspected test site, where the depth of the seabed is about 400 m. Subsequent analysis seems to support their initial conclusion. Nonetheless, some officials in the US defence and intelligence communities maintained for several months that the possibility of a nuclear explosion could not be ruled out, and cast doubt on the verifiability of the CTBT.²²

The Washington Times reported on August 28, 1997 that US defence officials believed the signals from the event had explosive characteristics and that the data gave "high confidence" that the activity detected was a nuclear explosion equivalent to between 100 and 1000 tonnes of TNT. Satellites had indicated the movements of trucks and other activities that had been seen prior to previous nuclear explosions at the main test site. A US plane with radiation detectors was sent to measure radioactivity downwind from the site on August 14 but detected nothing. The US defence officials apparently relied for location on data from a single station equidistant from the test site and the earthquake location, giving a location consistent with the test site.²³

The Russian government denied any nuclear testing, but noted they were carrying out hydrodynamic and subcritical experiments at the central test site. (Interestingly, the US was at the same time carrying out hydrodynamic tests at the Nevada Test Site. An earthquake of magnitude 4 occurred just beneath the Nevada Test Site on September 12, 1997.)

In early September, media reports said that AFTAC, the oversight body for the US National Data Center, had concluded that the event was located about 130 km from the test site, in the Kara Sea.²⁴ The US National Data Center supports US monitoring and verification capability and serves as a coordinating centre for data exchange between a number of US and foreign seismic stations and the pIDC (and, eventually, the IDC). In late September some defence officials were still calling the event "unresolved". On November 4, 1997 the CIA and the White House formally dropped their claim that the Novaya Zemlya event was a nuclear explosion, on the basis of a report by an independent panel.²⁵ However, the panel was unwilling to state definitely that the event was an earthquake.

²² *Arms Control Reporter*, 1997b.

²³ Smith, 1997a; Marshall, 1998; van der Vink *et al*, 1998.

²⁴ Sykes, 1997.

²⁵ Smith, 1997b.

The initial pIDC report, hours after the event, located the event offshore from Novaya Zemlya, fairly close to its ultimately determined location, based on six stations used by the pIDC. An ocean location is usually taken as strong evidence that the event was an earthquake. Also, an aftershock with mb of 2.4, or about 10 tonnes yield, about four hours after the initial event, with similar waveforms, was later found by Norwegian analysts who visually screened the seismic records.²⁶ Such aftershocks are characteristic of earthquakes. The pIDC gave an initial mb of 3.9. Later analyses seem to have settled on 3.5.

A detailed review of the event²⁷ indicates that the August 16 event was one of five since 1986 in the region of Novaya Zemlya that have been sources of interest. US defence officials claimed that four of the five were suspicious. All five, according to Sykes, have been shown to be earthquakes.²⁸ Sykes notes that all five earthquakes were quite small, showing that the monitoring capability for this region is good. From the signal-to-noise ratio of the August 16 event, it appears that events down to mb = 3.0 could be detected, corresponding to about 50 tonnes yield.²⁹

The IMS station closest to the event, ARCESS in northern Norway, was not operational. However, a non-IMS station in Finland was able to supply useful data. It also had a good archival record of seismic and explosive events from the Novaya Zemlya area.

From various signals, seismologists concluded that the original event had the waveform characteristics of other earthquakes which had occurred in the same area, but not those of nuclear explosions at the test site. British, Norwegian and independent US seismologists concurred from their analysis that the event was an earthquake.³⁰

The Norsar, 1997 report says that the event illustrates the difficulty of reliably locating and classifying a seismic event of mb about 3.5, even in a well-calibrated region. Bowers *et al*, 1997, note the importance of archived data and hence of maintaining operations at the stations that have such data. These seismologists believe that the event shows that the international monitoring system, as embodied in the pIDC, was indeed effective, even in prototype form. They urged that it be brought up to its full capability as soon as possible, and that it make optimal use of data and analysis from non-IMS stations.

Thus, the system worked well in this case. With some data from non-IMS stations, it detected an event of magnitude 3.5, about 50 to 100 tonnes equivalent yield and allowed for its identification as an earthquake under the Kara Sea. An aftershock equivalent to about 10 tonnes

²⁶ Norsar, 1997.

²⁷ Sykes, 1997.

²⁸ Norsar, 1997 says there was only one previous confirmed earthquake in this region, that of 1986.

²⁹ Richards and Kim, 1997.

³⁰ Bowers *et al*, 1997; Norsar, 1997; Sykes, 1997; van der Vink *et al*, 1998.

was also detected. Detection of both events was much better than the system's advertised identification threshold of magnitude 4. If the CTBT had been in force, the activity detected at the site could have given rise to on-site inspection to resolve any remaining doubts.

The inconsistent claims between the seismologists and the US defence officials probably reflect political positioning, at a time when the US President was submitting the CTBT to the Senate for its advice and consent. Some in the US Administration may have wished to signal that the US was watching test sites closely and would vigorously pursue any suspicious events. However, the Novaya Zemlya event illustrates the ways in which scientific results can be used for political purposes and underlines the need to develop processes that make full use of all available data, including non-IMS data, and submit it to open analysis and review.

4B. The Indian Explosions of May 11 and May 13, 1998.

On May 11, 1998, the Indian Prime Minister, Mr. Vajpayee, announced that India had set off three underground nuclear explosions at its test site in the Rajasthan desert: a fission device, a low-yield device and a thermonuclear device. He stated that yields were in line with expectations, though he was speaking only about an hour after the explosions, leaving little time to analyze results. There was no release of radioactivity. The explosions were said to be fully contained, like that of May 1974. The Chairman of India's Department of Atomic Energy later said the explosions were simultaneous and that the magnitudes were 12 kt for the fission device, 43 kt for the thermonuclear device, and 0.2 kt for the low-yield device. The 12 kt and 43 kt blasts were one km apart. The third was about 2 km away.³¹ The thermonuclear device was said to be a true two-stage weapon, not just a boosted fission device. The yield was kept low for a thermonuclear device in order to avoid seismic damage to nearby villages.

On May 13, India set off two simultaneous low-yield explosions, of 0.3 kt and 0.5 kt, in sand dunes at the same test site. The official statement said there was no release of radioactivity, somewhat surprising for an explosion in a sand dune.³² India said these tests were intended to improve India's capability to carry out subcritical experiments and computer simulations of weapons designs.

Simultaneous nuclear explosions are not new. The US and Russia have both set off a number of simultaneous explosions in the course of their testing. The incentives for multiple explosions are that they are cheaper to do at the same time and there is less likelihood of one test causing damage at a second test site before the second weapon can be fired. The signals can be disentangled under certain conditions, especially if local data is available. Multiple, but not quite simultaneous, explosions can also be used to test explicitly the impact of the effects of nuclear explosions on nearby nuclear weapons.

³¹ Bagla and Lawler, 1998; Marshall, 1998.

³² Findlay, 1998.

The signal from the May 11 explosions was readily detected by seismic stations around the world, including 62 stations used by the pIDC, which gave it a location close to that indicated by India. The magnitude estimated by the pIDC was 4.7. The magnitude estimated by an IRIS station at Nilore in Pakistan, 750 km from the explosions, was 5.1. The US Geological Survey, which operates a worldwide network, gave an initial estimate of 5.4, later modified to 5.2.³³ The Geological Survey of Canada detected the May 11 explosion at the Yellowknife seismic array and at other stations.

Using the 5.2 value, one source³⁴ estimates the yield to be about 12 kt, within a factor of about 2. No observers see any evidence for separate explosions on May 11. Comparisons of the waveforms of the 1974 and May 11 explosions, as recorded at Yellowknife, and found no evidence for source multiplicity.³⁵ This implies that if there were two large explosions, they went off within about a fifth of a second of each other. Since they were so close together in time and space, the total yield detected should correspond to the sum of the yields of the two main blasts, or 55 kt.

Even with errors, the yield detected was much less than that claimed by India. There is still much room for error in yield estimates and the test site region has not furnished a great wealth of historical explosion and earthquake data. Nonetheless, the yields estimated by the international networks raise questions about the size of the Indian blast. One aspect of interest is that it is unlikely that a true thermonuclear blast could have occurred if the total yield was only about 15-20 kt.³⁶ The primary trigger alone was estimated to have a yield of 12 kt.³⁷

The ratio in yields between the May 11 and the 1974 explosions is about 2. Most observers estimate the yield of the 1974 blast at about 6 to 8 kt. This would give a yield for May 11 of 12 - 16 kt.³⁸ A more recent analysis gives a mean yield estimate of 12 kt.³⁹

No evidence of the May 13 tests was detected by seismologists outside India, despite extensive scrutiny of the seismic records. The Nilore station was operating at the time. Using the signal to noise ratio of the May 11 explosion at Nilore, one source estimates that a magnitude

³³ van der Vink *et al*, 1998.

³⁴ *Ibid*.

³⁵ Wallace, 1998; Bent and McCormack.

³⁶ Wallace, 1998; Albright, 1998.

³⁷ *The Hindu*, 1998.

³⁸ Wallace, 1998.

³⁹ Barker *et al*, 1998.

as low as 2.5, corresponding to a yield of about 10 tonnes, should have been detected.⁴⁰ An upper bound of about 30 tonnes is suggested by one recent source.⁴¹

Scientists at the Bhabha Atomic Research Centre used a magnitude of 5.4 for the May 11 explosion and deduced a yield of 65 kt. This result was obtained by using a relationship appropriate for the Nevada Test Site, which would tend to exaggerate the yield. Using that relationship for the May 13 explosions would imply a signal of magnitude of 3.88, 50 times greater than background⁴² and thus clearly detectable.

Even if the blasts were set off in a very porous media that decoupled the yield by a factor of ten, the maximum yield that would go undetected would be about 100 tonnes. This is well below the 800 tonnes total claimed by India for May 13. Claims by Indian scientists that interference between simultaneous blasts might account for their low apparent yield are not convincing. Interference patterns in both space and frequency would have been detected by the 60 IMS stations that detected the May 11 explosions.⁴³

4C. The Pakistani Explosions of May 28 and May 30

Several weeks after the Indian explosions, Pakistan responded on May 28, with five tests, at a site near its western border with Afghanistan. The total announced yield was 40 to 45 kt, with the largest explosion being 30 - 35 kt. On May 30, Pakistan announced a sixth blast, with a yield of 15 - 18 kt. This was a single blast, although two explosions had been planned.

The explosions on May 28 were recorded by 65 stations used by the pIDC with a magnitude of 4.6, indicating a yield of about 10 kt. The USGS reported an mb of 4.8. The Geological Survey of Canada detected the May 28 Pakistani explosion at the Dawson City seismic array and other locations in northern and western Canada. Initially it was seen as a multiple (at least double) explosion, with yields for each of two events of 10 - 15 kt.

The May 30 event was recorded by 51 stations used by the pIDC with a magnitude of 4.3, indicating a yield of about 5 kt. The May 30 location was determined to be 100 kilometres from the first set of explosions.

Pakistan's intention was flagged when Nilore stopped transmitting data two hours before the first explosion.⁴⁴ Thus there is less close-in data than for the Indian explosions.

⁴⁰ van der Vink *et al*, 1998.

⁴¹ Barker *et al*, 1998.

⁴² Wallace, 1998.

⁴³ van der Vink *et al*, 1998.

⁴⁴ Marshall, 1998; van der Vink *et al*, 1998.

The waveforms from the Pakistani explosions on both days were more complex than the Indian explosions, and May 28 was more complex than May 30. This could be due in part to multiple explosions on May 28, but it could also be due to differences in the topography.⁴⁵

5. IMPLICATIONS OF THE THREE EVENTS FOR CTBT VERIFICATION

5A. *General Implications*

In each of the three events studied, the CTBT verification system, as it now exists in prototype form, did what it was supposed to do and achieved what might be reasonably expected of it at this stage of its development. Drawing on about 60 IMS seismic stations (six in the case of the relatively small Novaya Zemlya event), the pIDC quickly detected the principal events, located them with reasonable accuracy, and provided magnitudes.

The pIDC showed a capability, using both IMS and non-IMS seismic data, of detecting events down to about $m_b = 3$ or below, an order of magnitude below its design threshold. With its full complement of stations and networks operating, including those of non-seismic technologies, it can reasonably be expected that the pIDC (and eventually the IDC) would be able to do an even better job, especially if non-IMS data continues to be used.

Neither the pIDC, nor the eventual IDC, is expected to make judgements about the nature of events. Nonetheless, the data provided by the pIDC will be instrumental in helping States Party reach their own conclusions. It is hard for an outside observer to differentiate the role played in these cases by the IMS and the non-IMS stations. In any case it seems clear that the pIDC, and eventually the IDC and States Party, should make the best possible use of all available data, including that from non-IMS sources.

Looked at another way, it would be difficult for the CTBT verification system to ignore the wealth of data and analysis available from outside sources. Non-IMS networks provided very useful data in these three cases. The ability of a wide range of groups to obtain and use remote sensing data (eg. seismic data, satellite imagery, etc.) and analysis will clearly be a major factor in the future politics of arms control, including the CTBT. Many of these groups will have their own agenda. Some could be very useful supporters of the CTBT and its objectives.

Information will be an important resource. It will be important for Canada, as for other States party and for the CTBTO itself, to keep up with advances in the use of technology, and to have access to critical sources of current information and analysis, in order to speak and act credibly on issues of compliance with the CTBT.

The availability of information from outside the CTBT monitoring system, and its use by various groups for various purposes, raises the question of the confidentiality of the data used by

⁴⁵ Wallace, 1998.

the IDC. From the perspective of good science and of finding the best interpretation of events, a broad dissemination of the IDC's data would be most useful and beneficial, consistent with the confidentiality conditions under which it was acquired (e.g. commercially confidential information from mining companies about their blasting operations). IDC data will be of the highest quality and could serve to illuminate any discussions about the nature of unexplained events, especially as it will represent some of the most important input into conclusions drawn by States Party. Of course, countries will retain full control of any data generated by NTM.

5B. Specific Implications from the Three Cases

The Novaya Zemlya event is probably typical of anomalous situations that might arise under the CTBT: an event with some ambiguities close to a former test site, along with some NTM evidence of test preparations. The pIDC detected the event and supplied the location and magnitude within a reasonable range. It provided for identification of the event as an earthquake beneath the Kara Sea, 130 km from the test site, with $m_b = 3.5$, corresponding to a yield of or 50 to 100 tonnes if it had been an explosion. As noted above, a key IMS station in northern Norway, was not operational at the time, but a non-IMS Finnish station was able to supply key data. In-country IMS stations in Russia were a useful part of the network.

Outside analysts were able to detect an aftershock. (The pIDC screening would not have accepted the aftershock as an event. One source⁴⁶ suggests that this should be reviewed.) Under the CTBT, remaining concerns could have been dealt with by an on-site inspection.

Much of the controversy about the Novaya Zemlya event was within the US government, or between defence officials and groups of seismologists both inside and outside the US government. These latter groups seem fairly unanimous in their view that the event was an earthquake.

In the cases of the Indian and Pakistani tests, the pIDC detected and located the main explosions, and provided magnitudes. The pIDC did not detect the sub-kt explosions set off India and Pakistan, nor the simultaneous explosions above 1 kt in each case. This led to claims that the CTBT could not be adequately verified, on the grounds that militarily significant testing could be done at less than 1 kt and go undetected. Again, much of the debate was between groups within the US either supportive of, or opposed to, the CTBT.

It was well known in the negotiations leading to the CTBT that verification of the CTBT would be valid only down to some threshold and an m_b of 4 (corresponding to about 1 kt) was accepted as a reasonable target. In the three cases studied here, the monitoring system has clearly demonstrated that it could do better than that.

⁴⁶ Norsar, 1997

Given the signal-to-noise ratio for the main Indian explosion on May 11, the Nilore station should have seen explosions on May 13 as low as $m_b=2.5$, or about 10 tonnes. As in the story of the dog that did not bark, the fact that neither Nilore nor any other outside station registered the sub-kt Indian explosions of May 13 raises interesting questions, which are at this time unresolved. Either the blasts were more decoupled than appears to be the case, their yields were much smaller than announced, they did not take place, or the detection and calibration system failed in some yet-to-be-explained way.

Detecting simultaneous explosions is not essential for the purposes of the CTBT. One explosion is enough to constitute a violation of the treaty. The Pakistani sub-kt tests of May 28 and the Indian sub-kt test of May 11 were set off simultaneously with much larger explosions, making them very difficult to detect. Given that the system did not see the Indian sub-kt explosions of May 13 on their own, it is not surprising that it did not detect the sub-kt blasts set off simultaneously with larger blasts. Even larger blasts could be hidden from teleseismic observation in a 15 kt event if the delay in firing is less than 0.3 sec for 1 km separation.

5C. India and Pakistan as Test Cases

It should be stressed that the India and Pakistan explosions do not represent the kinds of situations that the CTBT monitoring system would likely have to deal with under the Treaty. This would be the case even if the system were fully operational, although a complete system would undoubtedly be more effective. Infrasound and hydroacoustic stations probably would not have added much in the Indian and Pakistani cases. Radionuclide monitoring, especially from close-in stations, might have helped to detect any venting that might have occurred. The nearest operating radionuclide station in the IMS network to India and Pakistan was probably in Kuwait, a good distance away.⁴⁷ However, there are also a number of institutional reasons why the system did not have the advantages it would have in seeking to detect clandestine nuclear explosions by States Party to the CTBT, as outlined below.⁴⁸

Despite conclusions by some analysts that sub-kt tests have little military value, India and Pakistan must have felt their sub-kt tests had military or political value, because they carried them out. However, their situation is different from that of States Party to the CTBT. Indian and Pakistan obtained the benefits of knowledge from both smaller and larger blasts because they did not fear detection. A State Party to the CTBT trying to conceal a test explosion would not set off a larger explosion and would be probably be constrained by fear of detection to the sub-kt range, of lesser military value by itself.

India and Pakistan are not signatories to the CTBT and are not bound by it. Monitoring of States Party (or signatories, prior to entry into force) would be much more effective, as they would agree to have monitoring stations on their territories. If they were States Party to the

⁴⁷ van Moyland and Clark, 1998.

⁴⁸ Findlay, 1998.

CTBT, India and Pakistan would have IMS monitoring stations under any reasonable arrangement. In-country seismic stations would considerably enhance the IMS network's ability to detect and identify low-yield explosions and, probably, to detect simultaneous explosions. It is noteworthy that Pakistan stopped the flow of information from the IRIS Nilore station prior to carrying out its tests, cutting off rather than enhancing the network's detection capability. A failure of an in-country CTBT station when a suspicious event occurred in that country would only heighten suspicions.

States Party to the CTBT would also be subject to requests for on-site inspections which would certainly help to clarify the kinds of verification issues raised by the Indian and Pakistani tests, and would be a strong deterrent to CTBT States Party concerned about detection.

Thus a complete CTBT verification system operating with respect to States Party to the CTBT after entry into force would have a number of detection advantages that were not available to the PIDC in the Indian and Pakistani cases. This strengthens the case for moving ahead.

5D. Advance Knowledge

One advantage that the verification system did have in the Indian and Pakistani cases, that it might not normally be expected to have, is that the explosions were largely anticipated, except the first one in India. Even that one was announced immediately after the event, along with its location, making retroactive searching easier.

While it was not necessary in these cases to have advance knowledge of the larger explosions in order to detect and identify them, advance knowledge would certainly be helpful. It could help to ensure that all the key monitoring stations would be on full alert (even though they are supposed to operate continuously in any event). The absence of ARCESS for the Novaya Zemlya event, and of Nilore for the Pakistani event, deprived the monitoring system of important information. While the silencing of Nilore was presumably deliberate, its absence in that case nonetheless makes the point that it is essential to have data from regional and in-country stations, whether IMS or not.

The reported failure of the US satellite detection and analysis system to detect test preparations was a controversial aspect of the Indian explosions, at least within the US. However, while advance notice would undoubtedly have been useful in terms of verification, as well as politically, this was not a failure of the CTBT monitoring system but of the US NTM. Previous Indian efforts to prepare for testing had been seen by the US in 1995 and were detectable using commercial imagery.

The Indians seem to have taken special pains to keep the May 1998 test preparations secret. They did not need to dig shafts, which were already in place from 1995. They reportedly synchronized their activities to take place at times when US satellites were not overhead. And they created an impression of military testing activity in other parts of the country in order to divert attention. Even so, the Indians may have been plain lucky that US attention briefly

wandered. The reported US failure may have arisen in part because of the overload of information.⁴⁹ The appropriate information may have been in the images, but hard-pressed analysts simply could not keep up. Potential violators of the CTBT could not count on such failures.

The Pakistani preparations at both test sites seem to have been thoroughly monitored. Satellites observed the pouring of concrete to stem the shafts to be used in the May 30 explosions. (As it turned out, only one device was exploded).

In retrospect, one wonders whether too much is being made of the reported US detection failure. If it represented a failure of US government expectations and system standards, then it should certainly be addressed in that context. But would a few days warning have been sufficient for the US and the world community to dissuade India from the tests? Vajpayee and his party had been committed to taking India nuclear for decades.⁵⁰ He had announced a review in March 1998, on his accession to power, of India's nuclear weapons policy, with a view to the induction of nuclear weapons into India's military posture. He was aware of the dissuasion that had occurred when test preparations were discovered in 1995. The actions of the US and other Western countries after the recent tests have not convinced India to renounce its nuclear ambitions (although they may help to channel them). It is not evident that the threat of those actions before the tests would have prevented them from going ahead. Again the point is that detection in advance is desirable, but can only go so far.

In the case of Novaya Zemlya, advance satellite information seems to have been available to US officials, but they may have misinterpreted it by analyzing it in isolation. Activities very similar to those preceding previous nuclear tests were spotted in the days before August 16, leading to strong suspicions that a test explosion was imminent. This activity, linked to the timing of the earthquake and its initial location compatible with the test site, may have led some officials to believe that the event was an explosion.

The lesson from the Novaya Zemlya case is that all available information should be used, from different sources and from different technologies, and that availability and open review of the full range of data and the analysis is the best route to the truth.

6. CONCLUSIONS

For the Nova Zemlya event, verification was a key issue, given that Russia had signed the CTBT. The outcome of the verification process determined whether the event would have larger repercussions. Fortunately, the CTBT seismic monitoring system was able to dissipate suspicions.

⁴⁹ *Trust and Verify*, 1998.

⁵⁰ Walker, 1996.

For the Indian and Pakistani explosions, the most important issues were and are the political incentives and disincentives that drove the countries to test, and the political will of the rest of the world to respond. These issues evolve in a very broad context of international and regional security and go well beyond the scope of the CTBT verification regime and of this paper. Verification was not a key issue, because neither India and Pakistan had signed the CTBT and because both countries had announced their tests. Nonetheless, the tests provide useful information about the CTBT verification system and vice versa.

The three cases studied in this paper suggest that components of the CTBT verification system – the IMS seismic monitoring networks and the pIDC – are working reasonably well at this early stage of implementation. This augurs well for the future. For low-yield events, the system has performed better than its design threshold. However, the case studies underline the need to use all available information in order to further improve the threshold for detection and identification and the overall effectiveness of the monitoring system.

Information from non-IMS sources could make a valuable contribution to CTBT verification. Both States Party and the CTBTO should develop a policy on the sharing of information and analysis with non-IMS sources and groups, and on both developing and using their skills. The broadest possible dissemination of information received and produced by the CTBT verification system should be promoted, consistent with agreements made with the providers of the information.

It would be useful to have a formal process for integrating the full range of available data and analyses, at both the national and the international level, and for its objective review. There would have to be assurances that any data used by the IDC met its standards, and protocols developed regarding the collection and use of data supplied by outside groups

The events reviewed in this report all show the importance of having regional and in-country stations as part of the seismic and other monitoring networks. They also show the utility of advance notice, which would help to ensure that the key stations were operating and ready to gather and transmit data.

One obvious broad conclusion is that the CTBT verification system would benefit greatly by completing the IMS networks and setting up a fully operational IDC in Vienna. So far only about half the stations are operational. It will be important to gain experience with the full network. While the monitoring system should be fully operational by the time of entry into force, it is nonetheless important to maintain the momentum of ratification by more signatories, including the United States and Russia because of their importance to the Treaty, and to support the drive of the CTBTO toward full competence.

It is also important for the CTBT to enter into force as soon as possible, so that the full legal weight of the Treaty is assumed by States Party, including the obligation to accept on-site inspections. Again, promoting more ratifications is a priority.

The CTBT monitoring system would benefit greatly from universal adherence to the Treaty, including India and Pakistan. That way, the monitoring stations would be global and continuous, with a much improved accuracy of detection and location, and a lower threshold of detection for low-yield tests. Of course, the political benefits of universal membership would be even greater.

The CTBTO should develop a capability to access and use satellite data. This would help to determine the need for on-site inspections as well as prepare for efficient and productive inspections when required. As well, broad use and judicious interpretation of satellite imagery could lead to greater transparency and confidence between countries, helping to reduce regional tensions. This was discussed at some length in the negotiations leading to the CTBT and the CTBTO was not given a mandate or resources to develop much capacity in this area. Nonetheless, on-site inspections are an essential aspect of the Treaty and the CTBTO will need every advantage that it can obtain in this area. It will also have to keep up with evolving technology and information if it is to maintain its credibility.

Canada and other States Party have a strong interest in the CTBT and in its verification system. The CTBT is a major step forward in nuclear arms control and its verification regime is unprecedented in scope and depth. Given its landmass and location, and its technological capability, Canada can make a very important contribution to the IMS networks and will want to maintain a close understanding of technological advances they make. It is desirable to develop the relevant skills and technology and to support excellence in these areas, as well as in satellite imagery and analysis, from the perspectives of both security policy as well as technological and commercial development .

The technologies used for CTBT verification (seismic networks, remote sensing, atmospheric and oceanic modeling, radiological detection) will also be important for resource and environmental management on a regional and global scale. Developing these technologies, sharing information and encouraging universities, scientific institutions, NGOs, and private firms to be actively engaged are essential.

Continuing research in both the scientific and the policy aspects of CTBT implementation should be encouraged. Scientific research would support capabilities in the technologies of verification, especially those pertinent to its land mass and resources. Joint scientific and policy studies might look at the applicability of verification techniques to environmental issues such as climate change and biodiversity. Policy research would focus on the effectiveness of the CTBT in reaching its objectives, barriers to its effectiveness and how they might be overcome, and the relation of the CTBT to other NACD initiatives. Studies that relate the different NACD instruments in a coherent way to overall strategic objectives for world security would be particularly useful both for governments and for public understanding.

States Party and the CTBTO will want to keep the technologies used by the IMS, and other relevant technologies, under periodic review, to ensure that the allocation of resources to them is optimal, both in individual States Party and in the CTBTO.

States Party should develop policies on the use of information generated by their own agencies and by the CTBT verification regime. While confidentiality must be respected, for example for information essential to national security or provided by private firms, a broad dissemination is desirable to improve understanding and support for the CTBT and its objectives.

States Party should also be active in, and keep a close watching brief on, the institutions created to verify the CTBT and other NACD treaties, to ensure that they are both effective and cost-effective. In this regard it is interesting that most treaties have their own international agencies and verification systems, and that States Party to these treaties often set up their own specialized national agencies and budgets to match. As the total international budget for verification of these treaties moves up toward the billion dollar range and as national verification budgets similarly increase, each State Party will have a strong interest in ensuring it is getting value for money from its own and international activities.

ANNEX A: LIST OF ACRONYMS AND ABBREVIATIONS

AFTAC	- (United States) Air Force Technical Applications Center, parent body of the US National Data Center
CIA	- (United States) Central Intelligence Agency
CTBT	- Comprehensive Nuclear-Test-Ban Treaty
CTBTO	- CTBT Organization, in Vienna,
DAE	- (India) Department of Atomic Energy
DFAIT	- (Canada) Department of Foreign Affairs and International Trade
FAS	- Federation of American Scientists
IAEA	- International Atomic Energy Agency, in Vienna
IDC	- International Data Centre (of the CTBTO)
IMS	- International Monitoring System (of the CTBTO)
IRIS	- Incorporated Research Institutions in Seismology , a private US network of seismic stations
kg	- kilograms
kt	- kilotonne of chemical high explosive equivalent
mb	- magnitude of the seismic signal for a compressional body wave
NACD	- Non-proliferation, arms control and disarmament
NATO	- North Atlantic Treaty Organization
NPT	- Nuclear Non-proliferation Treaty
NRCan	- Natural Resources Canada
NTM	- national technical means of verification, such as satellite imagery, electronic intercepts, etc.

- pIDC** - provisional International Data Center, operated by the US Department of Defence in Arlington, Virginia
- PTS** - Provisional Technical Secretariat of the CTBTO
- SPOT** - French satellite imagery system, available commercially
- sub-kt** - less than a thousand tonnes, or kilotonne, of chemical high explosive equivalent
- TNT** - Trinitrotoluene, a standard chemical high explosive (no longer much used in commercial blasting
- UK** - United Kingdom
- UN** - United Nations
- US** - United States of America
- USSR** - Union of Soviet Socialist Republics, the former Soviet Union
- VERTIC** - Verification Technology Information Centre

ANNEX B: CANADA'S CONTRIBUTION TO THE IMS

Canada will contribute 3 primary seismic stations: Lac du Bonnet, Manitoba; Yellowknife, North West Territories; Schefferville, Quebec), 6 auxiliary seismic stations (Iqaluit, Mould Bay and Inuvik, North West Territories; Dease Lake and Bella Bella, BC; and Sadowa, Ontario); 1 infrasound station in Lac du Bonnet, Manitoba; 1 hydroacoustic station (Queen Charlotte Islands, BC), and 4 radionuclide stations (Vancouver, BC, Resolute and Yellowknife, North West Territories, and St. John's, Newfoundland and Labrador). Given its geographic expanse and its close-in view of the US and Russia, Canada is an important contributor to the IMS. Like some other countries, Canada also has an extensive national seismic network, with stations operated by government agencies, universities and private firms.

Canada's IMS stations are generally operational, or will be soon, but are not yet fully certified in accordance with the CTBT. Thus, Canada is further along in its ability to contribute data than most signatories to the CTBT. Canada's National Authority for the implementation of the CTBT has been established by the following departments: the Department of Foreign Affairs and International Trade (DFAIT), Natural Resources Canada (NRCan), and Health Canada, with Environment Canada. The secretariat is within DFAIT. Health Canada will be responsible for radionuclide monitoring. A Test Ban Verification Unit within the Geological Survey of Canada, in turn within NRCan, is responsible for the other three technologies.

Canada has developed advanced capabilities in many of these areas, notably seismic and radionuclide, and has a strong national interest in being a leader in them, given their important policy and commercial applications.

ANNEX C. THE MEASUREMENT OF YIELD, THE DETECTION THRESHOLD, AND THE MILITARY SIGNIFICANCE OF TEST EXPLOSIONS BELOW THE THRESHOLD.

A. The Measurement of Yield

The magnitude of a seismic event is measured as the amplitude of the vibration, corrected for distance and geologic media. The magnitude generally used is “mb”, that of the compressional body wave. The ratio of mb to Ms, the amplitude of one of the surface waves, is one of the important discriminants between earthquakes and explosions. The magnitude is proportional to the log of the yield.

For magnitude-yield calibrations, it is essential to have reliable yields determined in a uniform fashion. The relation between the measured seismic magnitude and the yield of an event will vary from site to site because of the geologic differences. The relation can vary from author to author, as different methods of calculating it may be used. It can also vary with evasive measures. The relation between magnitude and yield at different sites is still a subject of investigation for some sites. Accurate numbers in the equation require an independent confirmation of the yield, which may not exist. A recent, representative and internally coherent set of relations for explosions that are well coupled to the surrounding rock mass is given below⁵¹, although it should be kept in mind that the yields in the Indian and Pakistani case are not known as objectively as desired in formulating such equations.

For stable geologic environments such as Kazakhstan and by extension India
 $mb = 4.45 + 0.75\log Y$, where Y is the yield

For Pakistan
 $mb = 4.1 + 0.75\log Y$

For the Nevada test site
 $mb = 3.95 + 0.75\log Y$

The relation for Novaya Zemlya would be closer to Kazakhstan's than to Nevada's.

As noted, the yield of nuclear explosions is measured in tonnes or kilotonnes (kt) of chemical explosive equivalent. (Because nuclear reactions are millions of times more intensive than chemical reactions at the atomic level, the actual amount of fissile material involved in a nuclear explosion is of the order of kilograms (kg) rather than kt.) From these equations, an explosion of 1 kt in Kazakhstan would give an mb of 4.45, whereas the same explosion in Nevada would give an mb of 3.95.

⁵¹

Wallace, 1998.

A difference of 0.5 in the magnitude corresponds to a factor of about 5 in explosive yield, which is very significant. It was not until the later 1980s that the difference in magnitude of 0.5 between the test sites in Nevada and in Russia, for tests of a given yield, was broadly accepted outside the seismic community. Before then, some in the West believed that Soviet blasts were much larger than they were and, as a result, that they violated the Threshold Test Ban Treaty signed by the USA and the USSR in 1974, which banned explosions by those countries above 150 kt.

With the appropriate corrections for geology, it was later concluded that the Soviet explosions were within, or very close to, the limit. Jointly verified explosions, access to data from in-country networks, and the release by the USSR of data on explosion yields helped greatly to calibrate the corrections and to determine the yield-to-magnitude relations for Soviet test sites.⁵²

In general, mb can be measured with an uncertainty that corresponds to a factor of about 1.5 in yield. Thus 95 per cent of the time, a true yield of 150 kt will give measured values between 100 kt and 225 kt. Use of regional wave magnitudes can reduce the uncertainty to 1.3 or 1.4.⁵³ For measurements of explosions in India and Pakistan by outside networks, the uncertainty in yield seems to be about a factor of 2. Part of the variability in the Indian and Pakistani cases is because of different contributing stations.

It is perhaps not surprising, in going through the literature, to find that different sources use different values for the parameters in the magnitude-versus-yield equations, even for a given site. Often mb or yield is quoted, but not both. It is not clear in many cases whether site-specific corrections have been applied. The pIDC publishes uncorrected values, but this fact is not always cited by sources using them. Since a difference of only 0.1 in magnitude corresponds to a difference in yield of a factor of 1.5, small differences are important. Clearly, this is an area for a non-expert to tread carefully. This paper uses sources, where available, that quote both magnitude and yield and that seem to take a systematic approach in relating yields to magnitudes.

B. Detection and Identification Thresholds: How Low Can You Go?

A very important question is the lower limit of seismic magnitude (the threshold) at which the seismic monitoring system can detect, locate and identify the source of particular explosions, because of the military implications of tests below this threshold, which might not be detected.

Detection is easier than identification, since it simply requires a signal sufficiently above the background noise to demonstrate that a seismic event has occurred. Identification requires

⁵² Richards, 1990/91; Sykes and Davis, 1987.

⁵³ Richards, 1990/91.

more detail on the shape and timing of one or more waveforms. Generally, identification requires magnitudes that are greater than for detection, but through the use of several techniques the identification threshold can be brought down close to the detection threshold.

If a number of good quality regional stations are available within a thousand kilometres of the source, events with yields down to a few hundred tonnes can be detected and probably identified, especially if there is a recorded history of seismic events, ideally both earthquakes and explosions, in the area of the source. (An irony of the CTBT is that future nuclear tests, now banned, would be useful for calibration. However, chemical explosions can substitute to a degree.) For instance in the Novaya Zemlya event discussed below, the main event of $mb = 3.5$, corresponding to 50 to 100 tonnes of high explosives, was identified clearly as an earthquake by seismologists. An aftershock of only 10 tonnes, characteristic of earthquakes, was also detected and located.

By way of comparison, the car bomb that killed 28 people in Omagh, Northern Ireland on August 16, 1998, was reported to have a mass of 225 kg. The truck bomb that destroyed the US embassy in Nairobi on August 7, killing 200 people, was reported to have weighed 800 kg. The truck bomb that blew up the Federal Building in Oklahoma City several years ago may have weighed up to a few tonnes. The chemical explosives used to compress and detonate nuclear weapons generally weigh up to about 100 kg. One source⁵⁴ notes that tests at low nuclear yields use 50 to 100 lb of chemical high explosives. Reports of subcritical tests carried out by the US in 1997 and 1998 indicate a range up to 100 kg.⁵⁵

The detection capability of a given network is best shown as a map with a series of contours, where each contour represents a different level of detectability or identifiability. With good design, the regions of lowest threshold can be made to coincide with the regions of greatest detection interest.⁵⁶ However, a global monitoring system such as the one predicated by the CTBT is not intended to target particular regions.

As one goes to lower thresholds, the number of earthquakes increases rapidly, rendering the logistics of screening each event more difficult. Also, at lower magnitude, the differences between earthquakes and explosions tend to become more blurred, further complicating the analysis.

For mb equal to or greater than 4, there are about 7500 earthquakes per year, or about 20 per day.⁵⁷ The pIDC is currently detecting and locating about 100 seismic events per day, suggesting a detection threshold well below $mb=4$.⁵⁸ One of the limiting factors for identification

⁵⁴ Cochran and Paine, 1995.

⁵⁵ *Arms Control Reporter* 1997a, and 1998a.

⁵⁶ Sykes and Davis, 1982.

⁵⁷ Richards and Zavales, 1996.

⁵⁸ van ver Vink *et al*, 1998.

at the few-hundred-tonne level is the number of chemical explosions that occur in this range, mainly for open-pit mining and construction. This is why the CTBT provides that single chemical explosions of 300 tonnes or more are to be reported to the IMS as a confidence-building measure, if possible in advance. Such blasts are rare. The CTBT encourages the voluntary reporting of "other" chemical explosions greater than 300 tonnes, with respect to sites, profile and frequency, nature of the activity, and any other relevant detail. The "other" explosions mean ripple-fired explosions, where a large number of smaller blasts are set off in rapid sequence. The total yield is the relevant criterion. Such blasts are common in open-pit mining and in construction.

There is some uncertainty about the threshold for detection and identification when evasive measures, such as decoupling, are taken. Decoupling can be achieved by setting off the explosion in a large cavity or in loose, unconsolidated material such as alluvium. Cavity decoupling can reduce the signal amplitude for a given yield by a factor of up to 70 at a particular frequency, although to do so for large explosions would require very large cavities, and decoupling by cavity is probably not feasible for explosions of more than about 5 kt yield. The higher frequency regional waves are less susceptible to decoupling, again emphasizing the importance of regional stations. Also, the construction of a large cavity could attract attention in its own right. Smaller decoupling factors, of the order of 10, are considered more likely.⁵⁹ If an explosion of 5 kt were decoupled by a factor of 10, the signal would look like an explosion of 500 tonnes, which is close to the threshold of detectability.

C. The Detection Threshold for the CTBT and the Military Significance of Low-Yield Tests

The existence of a range of sub-kilotonne explosions that might not be detected by the CTBT seismic monitoring network raises the question of the military significance of such explosions. The CTBT bans only nuclear explosions, not other tests or preparations that could lead to the development of nuclear weapons, but do not themselves result directly in nuclear explosions. For NNWS Party to the NPT, such non-nuclear-explosive tests are already banned. However, the NWS believe that they would be allowed, under the CTBT, to carry out tests of weapons components, such as the chemical explosives that produce the implosion of nuclear-explosive material. (Not all CTBT signatories agree.) Such tests could include some fissile material in the core in order to study its properties under compression, as long as the material does not go critical, that is become involved in a sustained, prompt chain reaction resulting in nuclear energy release.

By way of definition⁶⁰, a hydrodynamic test produces no nuclear yield. Fissile material may be involved in order to study its physical properties but the fissile material does not participate in a nuclear chain reaction that would release nuclear energy. The term "hydrodynamic" refers to a system in which the material flow is described by hydrodynamic or

⁵⁹ Sykes, 1996.

⁶⁰ Garwin, 1997.

fluid equations. The US maintains that hydrodynamic tests are permitted under the CTBT. A subcritical test involves fissile material in masses and configurations that have no chance whatever of achieving criticality. Such tests are also considered to be permitted.

A hydronuclear test is one that could be accompanied by a limited nuclear chain reaction. Originally these tests were intended to determine whether a weapon was one-point safe, that is whether a detonation at a single point in a nuclear weapon could result in a large explosion. Some hydronuclear experiments could involve yields that range from milligrams of high explosive equivalent up to a few hundred tonnes. Hydronuclear tests are generally considered to be banned under the CTBT.

Hydronuclear experiments could be of use to incipient proliferators in helping to determine the optimum time for external triggering of the chain reaction and the initial post-critical dynamics of the explosion. In these and other cases they could serve to verify computer codes. However, they are less effective than actual tests in verifying the predictions.

The NWS have apparently concluded that they can maintain their stockpile without resorting to hydronuclear tests. In the negotiations leading to the CTBT, they each wished to maintain a low-yield threshold to allow further testing. The United States wanted a few kg, the British a few hundred kg, the Russians a few tonnes, and the French a few hundred tonnes.⁶¹ The US agreement to a zero-yield approach in 1995 helped move the CTBT process forward. Together, the NWS concluded that hydrodynamic tests, computer simulations, non-explosive component testing, and the large data base from previous test explosions could ensure them the data they need to maintain the safety and reliability of their weapons.

The US carried out two subcritical tests at Nevada in 1997. One used about 75 kg of chemical explosives and 1.5 kg of plutonium, the other 100 grams of high explosive and 140 grams of plutonium. The tests were to study the properties of plutonium under shock wave compression. Further tests were carried out in March and September 1998, using 100 kg of chemical explosives and about 1 kg of plutonium in the first, and 7 ounces of chemical explosives and a "small amount" of plutonium in the second.⁶²

While these tests might not violate the CTBT, they have nonetheless given rise to criticism, as representing a desire on the part of weapons states to maintain and improve their nuclear weapons technology. Similar criticisms have been made of inertial confinement experiments using focussed, pulsed lasers to produce small nuclear explosions in pellets less than a millimetre in diameter. These experiments are essential to the development of one form of civilian, commercial fusion reactor.

⁶¹ Cochran and Paine, 1995.

⁶² *Arms Control Reporter*, 1997a, 1998a, 1998b.

The US subcritical tests were carried out underground. Russia may have done similar tests at Novaya Zemlya. The US has indicated that methods are available to measure even milligrams of yield. Creating transparency in these experiments by making such data available, and by testing in above-ground containment vessels, would help to assuage fears that such tests could be used to mask larger-yield tests.⁶³

Some NNWS are concerned that the NWS can use such experiments, coupled with their computing capabilities and data bases, to develop new weapons. Nonetheless, it is the view of many experts in the field that new weapons would require full scale testing before one could have a high level of confidence in them.

Another reason for testing in the range of ten to a few hundred tonnes would be to develop weapons with a high yield-to-weight ratio suitable for tactical applications using short range missiles. In the case of India and Pakistan, larger explosions could be counterproductive in any conflict between the two countries, given their proximity to each other. It was presumably the desire to demonstrate prowess in this area that led both India and Pakistan to claim sub-kt explosions as part of their testing. Smaller weapons in most cases require more advanced technology, to achieve miniaturization and high yield-to-weight ratio.

The use of fusion materials to “boost” the fission yield of fission primaries, and increase their yield-to-weight ratio, would require testing to ensure a high level of confidence. So would two-stage thermonuclear weapons, in which the fission primary (probably boosted) serves to ignite a fusion reaction which provides the main explosive energy. India claimed that its main blast on May 11 was a true two-stage thermonuclear weapons. Tests of boosted fission primaries would most likely result in releases greater than one kt, and would therefore be readily detectable.⁶⁴ As noted, tests of thermonuclear weapons would likely give yields above 10 - 15 kt.⁶⁵

D. Past Tests

It is interesting to look at the past record of nuclear tests, as it may indicate the course countries will take to developing nuclear weapons in the future, even though advances in technology, computing and the availability of information suggest that the future will not repeat the past exactly. In retrospect, an effective detection threshold of 1 kt would have captured the great majority of tests by the weapons states in the past.

Most first tests were in the 10 to 100 kt range. The Indian and Pakistan tests fall into the low end of this range. Of the 1100 or so discrete nuclear explosions set off by the USSR, about 100 of them were less than 1 kt in yield. Of these, 90 involved hydronuclear experiments under

⁶³ Garwin, 1997.

⁶⁴ Coalition, 1998.

⁶⁵ Wallace, 1998.

100 kilograms of yield. About one third of these were one-point safety tests, in which the chemical explosive charges were exploded at one point only, to show that the yield was small, and therefore that the device was safe against such local explosions.

The US also set off about 1100 explosions in total, from 1945 to 1992. Of these 88 were one-point safety tests, mostly at very low yields but some at yields of tens or even hundreds of tonnes. In addition, there were about 50 hydronuclear tests, not counted as nuclear explosions.

The primary fission triggers for two stage thermonuclear weapons seem to have yields of greater than 10 kt. The average for the USSR, from its testing record, seems to have been about 18 kt. The Indian claim for its fission primary on May 11 was about 12 kt.

Strategic warheads deployed by the US and the USSR (and now by Russia) range from 40 kt up to about 1 megatonne, although none have been tested above 150 kt since the bilateral Threshold Test Ban Treaty of 1974.

The US typically used some six nuclear explosions in the development of each new model of nuclear weapon, while France reportedly used some 22 per model.⁶⁶ To the extent that potential proliferators need a series of tests to prove their weapons design, the possibility of detection increases significantly.

⁶⁶ Garwin, 1997.

ANNEX D. NON-SEISMIC TECHNOLOGIES IN THE CTBT MONITORING SYSTEM

A. Radionuclide

The IMS radionuclide monitoring system is an outgrowth of a global environmental monitoring network. By measuring the radioactivity in air samples, it would detect radioactive debris from atmospheric testing and from significant venting of underground or underwater tests. Concerns about radioactive fallout from atmospheric nuclear testing was a major reason for the Limited Test Ban Treaty of 1963.

Radiation can be detected in very minute quantities, and molecules or particulates in the atmosphere are easily dispersed. A global network should be very sensitive to any radioactive debris emitted or vented by a nuclear test explosion. Different kinds of radiation can be measured (alpha, beta, gamma), and their energy spectra recorded, allowing identification of the isotopes present. The kinds of fission product produced in a nuclear explosion are in many cases unique. Radionuclide monitoring is the only one of the four systems that can give definitive proof that a nuclear explosion has occurred.

The mechanism for transporting the radioactive material is essentially movement through the atmosphere – convection upwards and dispersion laterally. Clouds of radioactive debris would be widely dispersed in the southern and northern hemispheres by the prevailing winds. In the tropics there is less dispersion because of weaker horizontal movement.

Radionuclide monitoring is a slow process, even if recorded in real time. Transport from the source to a distant detector may take several days, or more in the tropics, during which time the radiation will decay. Isotopes with very short half lives are likely to have limited use for a global monitoring network. As with seismic networks, it is desirable to have radionuclide stations as close as possible to the source, to get a stronger signal, but this has to be traded off against global coverage.

Atmospheric models are very effective in predicting the dispersion of a given emission of radiation from a source. They are less effective at extrapolating backwards from detected radiation to identify a source location. Atmospheric modeling will undoubtedly improve with the work being done on global climate change, but radionuclide monitoring will remain a fairly indirect method of locating sources at long distances.

One source⁶⁷ suggests the IMS radionuclide monitoring system could locate sources within 1,000 km for a single particle, but would be less accurate for a larger release. Regardless of the error estimate, he cautions against using it as an operational tool for providing an ultimate geographical location.

⁶⁷ Desatio, 1997.

The radionuclide network which forms part of the IMS could be supplemented by national technical means. Aircraft could fly sorties in areas to take samples in areas where radiation is suspected. Black box detectors could be located close to known or suspected test sites, and the data transmitted automatically to data centres.

Atmospheric tests now seem unlikely, although such tests might still be difficult to detect in some circumstances. There is still controversy about an unexplained atmospheric event over the Indian Ocean in 1979. Many experts believe that it was a nuclear test explosion.⁶⁸ Atmospheric testing could be attractive if it were believed that location abilities are poor or so slow that tests offshore might be detected, but too late for attribution. Clandestine testers are also likely to take precautions against venting from underground tests. However, a number of US underground tests, and a fairly high proportion of Russian tests, are believed to have vented, some of the latter significantly. It would take significant venting for the test to be detected by radionuclide stations at long distances from the test site. Nonetheless, it seems prudent to have an effective radionuclide monitoring system. Its sensitivity and its precise identification of radionuclides make it potentially valuable. It was a Swedish radionuclide monitor, associated with a nuclear power station, that first detected radiation from Chernobyl. A Swedish network also detected xenon from a Russian nuclear test explosion in 1990, which the Russians themselves believed had not vented.⁶⁹ Sensitive radionuclide networks could have other useful purposes, although they might also be seen as intrusive in detecting activities not directly related to the CTBT.

Underground nuclear explosions create intense radioactivity underground. Some of the radioisotopes, which may be different from those created in an atmospheric test, find their way to the surface, sometimes long afterward, and from there into the atmosphere. They could be useful indicators of explosions, but are probably most detectable, because of the low concentrations, at relatively short distances or during an on-site inspection.

B. Hydroacoustic

Hydroacoustic sensors are designed to pick up sound waves in the ocean. As such they will detect explosions in the ocean or very close to its upper and lower boundaries – the atmosphere and the seabed – to the extent that energy from outside explosions is coupled into the ocean. Hydrophones tend to be sensitive to ocean explosions relative to the signal they receive, so that ocean explosions are heard very clearly around the world. A relatively sparse network of stations is sufficient. Since about 70 per cent of earthquakes occur under the seabed, it is important to have techniques and data for screening them out. A hydroacoustic network will contribute greatly to the screening process, by being less sensitive to non-explosive events.

⁶⁸ *Arms Control Reporter*, 1997c; Scott, 1997, Albright, 1998.

⁶⁹ de Geer, 1996.

Sound propagation in the ocean is complex and most waves travel on multiple paths from a source to a detector. The velocity varies with temperature, salinity and pressure. There will be reflections within layers of the ocean, and from the surface and the seabed, which of course varies in depth and structure. Energy from an explosion in the ocean will be transmitted into the seabed and back out again into the water.

For location, one source⁷⁰ suggests that a hydrophone network could locate ocean explosions within 10 - 20 km. This estimate appears to be for tests in the open ocean, within line-of-sight of one or more stations. This author believes that a hydroacoustic network should concentrate more on the southern hemisphere, where there is more ocean and less scope for land-based seismic networks. However, the locations of hydrophones in the CTBT monitoring system are fixed by the Treaty.

C. Infrasound

The infrasound network is intended primarily to detect explosions in the atmosphere or explosions near the surface of the ground or of bodies of water that are well-coupled to the atmosphere. One source⁷¹ suggests that an infrasound network could detect events down to 900 tonnes. Another author⁷² concurs, suggesting a detection threshold of about 1 kt at distances between 2000 - 3000 km. Thus infrasound waves from explosions travel remarkable distances. It is expected that ripple-fired (sequential) explosions from blasting at open pit iron ore mines in Labrador, which total a few hundred tonnes over a few seconds, will be heard at infrasound stations at Bermuda or at Thule, Greenland.

The infrasound network supplements radionuclide monitoring by providing rapid reporting. One source⁷³ suggests that it could locate explosions within about 100 km. Good location depends on good atmospheric models. Infrasound has a low false event rate for distinguishing between large explosions and other sources of sound, but at the 1 kt level experience is limited, and the false event rate is unknown.

⁷⁰ Zabaluev, 1996.

⁷¹ *Ibid.*

⁷² Simons, 1996.

⁷³ Simons *et al*, 1996.

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