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Nuclear Test Ban Verification: Recent Canadian Research in Forensic Seismology

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prepared for The Arms Control and Disarmament Division
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Canada

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The cover graphic is based on an ancient Egyptian hieroglyph representing the all-seeing eye of the powerful sky god, Horus. Segments of this "eye in the sky" became hieroglyphic signs for measuring fractions in ancient Egypt. Intriguingly, however, the sum of the physical segments adds up to only 63/64 and, thus, never reaches the equivalent of the whole or perfection. Similarly, verification is unlikely to be perfect.

Today, a core element in the multilateral arms control verification process is likely to be the unintrusive "eye in the sky", represented by a space-based or an airborne remote sensing system. These overhead imaging techniques will have to be supplemented by a package of other methods of verification including ground-based sensors and some form of on-site inspection and observations. All these physical techniques add together, just as the fractions of the eye of Horus do, to form the "eye" of verification. Physical verification, however, will not necessarily be conclusive, and there is likely to remain a degree of uncertainty in the process. Adequate and effective verification, therefore, will still require the additional, non-physical, element of judgement, represented by the unseen fraction of the eye of Horus.

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Table of Contents

List of Figures

Abstract

This report describes: a) verification and its rationale; b) the basic tasks of seismic verification; c) the physical basis for earthquake/explosion source discrimination and explosion yield determination; d) the technical problems pertaining to seismic monitoring of underground nuclear tests; e) the basic problem solving strategy deployed by the forensic seismology research team at the University of Toronto; and f) the scientific significance of the team's research.

Seismology provides the primary means for monitoring nuclear explosions that take place underground. Improved seismographic hardware, Canadian research expertise, and the availability of a vast "proving ground" (the Canadian land mass which bears close resemblance with other regions of nuclear test ban verification interest), are all helping Canada become an increasingly notable contributor to this highly specialized branch of forensic seismology.

The research carried out at the University of Toronto since November 1985 has two components: a) teleseismic verification using P wave recordings from both the old and the recently refurbished Yellowknife Seismic Array (YKA); and b) regional (close-in) verification using high-frequency L_g and P_n recordings from the Eastern Canada Telemetered Network, a group of stations installed to record earthquakes.

Analysis of more than 600 explosion-generated teleseismic records from the YKA has shown major differences in P wave attenuation among the propagation paths connecting this quiescent listening post with seven active nuclear explosion testing areas in the world. By taking advantage of the YKA's voluminous body of archived nuclear explosion data and of newly available signal analysis techniques, we have been able to make significant revisions to previously published P wave attenuation results for the same paths.

To appreciate the magnitude of these revisions, we have shown that explosion yield estimates inferred from the YKA data using previous and our revised attenuation values differ by a factor as large as 2, depending on the nuclear test site location. To understand the significance of the revisions from yet another perspective, we have performed analysis of YKA explosion data using our new attenuation values. The study has resulted in instances in which a seismic source depth indicator (a seismic phase known as pP) is successfully unmasked in the signals from underground nuclear explosions.

To improve the accuracy of rapid teleseismic locations of distant seismic events, we have carried out an in-depth study of systematic biases between the array-derived locations and those determined using global seismic network

readings. This study, based upon the analysis of recordings of more than 7,000 earthquakes, has resulted in the delineation of systematic location correction terms. Application of these correction terms will help facilitate reliable and speedy (from 20 minutes to one hour) epicentral determination of any well-recorded seismic event occurring within a 10,000 kilometre radius of the YKA.

The data-intensive approach described above is complemented by the development of a new method of signal identification and processing. Rooted in recent advances in mathematical engineering, the "oriented energy approach" has been introduced by the University of Toronto team into seismic wavefield analysis, taking advantage of the recent availability of the three-component, broadband recordings of the refurbished YKA. Preliminary investigations have shown that the new approach facilitates effective recognition of signals which are buried in noise.

The above teleseismic verification research is carried out in parallel with regional (close-in) verification research aimed at monitoring low-yield nuclear explosions using seismic network stations outside and inside the territory being monitored. Our regional research focuses upon the propagation, attenuation, geological distortion (site effects) of two regional seismic waves — L_g and P_n — of paramount importance in nuclear test ban verification.

A novel technique for measuring the decrease in energy over distance (i.e. attenuation) for L_g waves has been developed and successfully tested in the low-attenuating Canadian Shield. We have shown that the new technique is capable of detecting a minute amount of attenuation suffered by the L_g waves over Canadian Shield paths as short as 100 km — in the presence of conspicuous site-related differences. Spatial resolution on this scale is a valuable asset in monitoring low-threshold nuclear test ban treaties.

Development of an effective method for measuring P_n attenuation proves to be more challenging. Unlike other seismic phases, the P_n propagation mode, and hence the manner in which its energy spreads out geometrically (a phenomenon unrelated to attenuation), is poorly known. The uncertainty concerning the P_n geometrical spreading rate is well known to be a major source of error in the determination of the P_n attenuation. We have recently completed the development and testing in the Canadian Shield of a method for simultaneous determination of the P_n attenuation and the P_n geometrical spreading rate.

In order to preserve "earthquake-like" and "explosion-like" signature characteristics of arriving L_g and P_n waves and to "standardize" the station site amplification factor for reliable yield estimation, we have striven to overcome the problem of near-station signal distortions due to structure complexities near the station. Standardization schemes have been developed for both L_g and P_n waves.

For demonstration purposes, we have used the standardization scheme for L_g site effects to construct a new method of network calibration. By effectively turning network stations (instrument plus station geological site effects) into nearly identical "clones", fewer recording stations are required per seismic event for positive source identification and reliable yield estimation. In effect, we have been able to achieve a reduced source identification threshold.

Résumé

Sont décrits dans ce rapport : a) la vérification et sa raison d'être; b) les rôles fondamentaux de la vérification sismique; c) les paramètres physiques qui permettent de faire la distinction entre un tremblement de terre et une explosion, et d'évaluer la puissance d'une explosion; d) les problèmes techniques que présente le contrôle sismique des essais nucléaires souterrains; e) la stratégie fondamentale de règlement des problèmes appliquée par l'équipe de chercheurs en sismologie expérimentale de l'Université de Toronto; enfin, f) la valeur scientifique des recherches de cette équipe.

La sismologie offre le principal moyen de surveiller les explosions nucléaires souterraines. Un appareillage sismographique perfectionné, le savoir-faire des chercheurs canadiens et l'existence chez nous d'un vaste «polygone d'essai» (la masse continentale canadienne ressemble beaucoup à d'autres régions d'intérêt pour la vérification d'une interdiction des essais nucléaires), voilà autant d'atouts qui contribuent à faire du Canada un intervenant de plus en plus en vue dans ce domaine très spécialisé qu'est la sismologie expérimentale.

Les recherches menées à l'Université de Toronto depuis novembre 1985 comportent deux volets : a) la vérification sismique à distance à l'aide d'enregistrements d'ondes P fournis par l'ancien et le nouvel Ensemble sismologique de Yellowknife (ESY); b) la vérification régionale (à rayon rapproché) avec des enregistrements d'ondes à haute fréquence L_g et P_n fournis par le Réseau de télémétrie de l'est du Canada, un groupe de stations installées pour enregistrer les tremblements de terre.

L'analyse de plus de 600 enregistrements (ESY) d'ondes sismiques engendrées par des explosions très éloignées a révélé d'importantes différences dans l'atténuation des ondes P le long des trajectoires de propagation reliant ce poste d'écoute passif à sept zones actives d'explosions nucléaires expérimentales dans le monde. En puisant dans les très nombreuses données d'archives de l'ESY sur les explosions nucléaires et en recourant aux nouvelles techniques d'analyse des signaux, nous avons pu réviser de façon significative les résultats publiés antérieurement au sujet de l'atténuation des ondes P pour les mêmes trajectoires.

Pour avoir une bonne idée de l'ampleur de ces révisions, nous avons montré que les estimations de la puissance des explosions, établies à partir des données de l'ESY en utilisant les valeurs d'atténuation antérieures puis nos valeurs révisées, peuvent varier du simple au double selon la localisation de la zone d'essai. Pour comprendre la portée des révisions d'un autre point de vue, nous avons analysé les données de l'ESY sur les explosions en appliquant nos nouvelles valeurs d'atténuation. Nous avons ainsi pu, dans certains cas, voir apparaître

effectivement une indication de la profondeur du foyer (type de signal appelé pP) dans les signaux produits par des explosions nucléaires souterraines.

Afin d'améliorer la précision des relevés rapides d'événements sismiques éloignés, nous avons étudié en profondeur les écarts systématiques existant entre les relevés obtenus à partir des données de l'ESY et ceux établis d'après les enregistrements du réseau mondial de stations sismologiques. Notre étude, qui se fonde sur l'analyse des enregistrements de plus de 7 000 tremblements de terre, a permis de fixer des paramètres correctifs systématiques de localisation. L'application de ces paramètres aidera à localiser de façon fiable et rapide (entre vingt minutes et une heure) l'épicentre de tout événement sismique dûment enregistré se produisant dans un rayon de 10 000 kilomètres de l'ESY.

Cette approche, qui est fortement axée sur l'exploitation de données, est complétée par l'élaboration d'une nouvelle méthode d'identification et de traitement des signaux. La «méthode à énergie orientée» *(oriented energy approach)*, s'inspirant de récents progrès dans le domaine du génie mathématique, a été appliquée par l'équipe de l'Université de Toronto à l'analyse des champs d'ondes sismiques; les chercheurs ont profité des enregistrements à triple composante en large bande qu'offre depuis peu l'ESY modernisé. Les travaux préliminaires ont montré que cette nouvelle méthode permet de mieux capter les signaux en dépit des bruits ambiants.

Les recherches susmentionnées sur la vérification d'événements sismiques éloignés sont menées parallèlement à des travaux régionaux (à rayon rapproché) dont l'objet est de surveiller les explosions nucléaires de faible puissance grâce à des stations sismologiques situées à l'extérieur et à l'intérieur du territoire visé. Nos études régionales se concentrent sur la propagation, l'atténuation, la distorsion géologique (effets locaux) de deux ondes sismiques régionales — L_g et P_n — qui revêtent une extrême importance pour la vérification d'une interdiction des essais nucléaires.

Une nouvelle technique pour mesurer l'affaiblissement de l'énergie des ondes L_g en fonction de la distance (atténuation) a été élaborée et mise à l'essai avec succès dans le bouclier canadien, dont l'effet d'atténuation est faible. Nous avons montré que la nouvelle technique permet de détecter, dans le cas de ces ondes, des atténuations infimes sur des distances aussi courtes que 100 kilomètres le long de trajectoires de propagation dans le bouclier canadien — même en présence d'écarts manifestes provenant de la topographie. Une résolution spatiale de cet ordre constitue un atout précieux pour contrôler l'observation de traités interdisant les essais nucléaires à faible puissance.

Il est plus difficile de mettre au point une méthode efficace pour mesurer l'atténuation des ondes P_n. Contrairement à ce qui vaut pour d'autres types de signaux sismiques, on connaît mal le mode de propagation de ces ondes, et partant, la manière dont l'énergie se déplace géométriquement (phénomène qui n'a rien à voir avec l'atténuation). L'incertitude quant au taux de propagation géométrique des ondes P_n, on le sait fort bien, constitue une grande source d'erreurs dans le calcul du degré d'atténuation de ces ondes. Récemment, nous avons terminé, dans le bouclier canadien, la mise au point et l'essai d'une méthode permettant de calculer simultanément le degré d'atténuation et le taux de propagation géométrique de ces ondes.

Afin de fixer la signature des ondes d'arrivée L_g et P_n selon qu'elles émanent d'un tremblement de terre ou d'une explosion, et de «normaliser» le facteur d'amplification de la station de manière à obtenir une estimation fiable de la puissance, nous nous sommes efforcés de surmonter le problème de la distorsion des signaux qui se produit à proximité de la station en raison de la complexité des structures situées aux environs. Des schèmes de normalisation ont été mis au point, aussi bien pour les ondes L_g que pour les ondes P_n.

Pour les besoins de la démonstration, nous avons appliqué le schème de normalisation aux effets locaux des ondes L_g afin d'élaborer une nouvelle méthode de calibrage du réseau. En transformant les stations du réseau (effets des instruments et effets de la géologie des lieux) en «clones» quasi identiques, on réduit le nombre de stations enregistreuses nécessaires pour repérer avec certitude la source d'un événement sismique et faire une estimation fiable de sa puissance. Nous avons pu ainsi abaisser le seuil d'identification de la source.

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List of Abbreviations

BB	Broad-band
CTBT	Comprehensive test ban treaty
GSE	Group of Scientific Experts
GSETT-2	Group of Scientific Experts: Technical Test-2
HF	High frequency
km	Kilometre(s)
L_g	L_g wave
LYTTBT	Low yield threshold test ban treaty
m	Metre(s)
m_b	Body wave magnitude
M_s	Surface wave magnitude
NRDC	Natural Resources Defense Council
NTM	National technical means
PSM	Power spectral method
P_n	P_n wave
RTSM	Reversed two station method
S/N	Signal to noise ratio
TTBT	Threshold test ban treaty
YKA	Yellowknife Seismic Array

Chapter 1: Introduction

Toronto, Ontario, Canada was the host city of the 1957 meeting of the International Association of Seismology and Physics of the Earth's Interior, at which an address was given on seismological aspects of nuclear explosions. It was also at this meeting that the first public release was made of the source details of a scheduled nuclear explosion in Nevada. This explosion, code-named Rainier, took place 250 m below the Earth's surface on September 19, 1957. There have been well over 1,000 underground nuclear explosions worldwide since then; roughly half of them have taken place since the 1974 signing of the Threshold Test Ban Treaty by the U.S.A. and U.S.S.R, which bans underground nuclear testing by these two countries with yields of more than 150 kilotons. Most of these underground nuclear explosions have been weapons tests.

Verification, or more precisely, what constitutes adequate verification, has been the most contentious technical issue of the test ban debate. More than 30 years have elapsed since the 1958 conference of experts in Geneva — the first significant East-West meeting to discuss the technical aspects of seismic verification — during which time considerable progress has been made in the field of forensic seismology. Nevertheless, the world today is still without a comprehensive test ban treaty (CTBT), nor is it within unobstructed sight of such a treaty. One reason for the failure to bring about a CTBT continues to be concerns over adequate verification of compliance with test ban treaties.

The purpose of this report is to summarize the highlights of seismic verification research undertaken at the University of Toronto on behalf of the Verification Research Program of External Affairs and International Trade Canada. The results reported here are drawn partly from recently published scientific articles, partly from scientific articles which are in press as of July 1991, and partly from unpublished findings connected with our ongoing research activities. Being intended for a broad spectrum of readership, this report is written with fewer technical terminologies than one typically encounters in formal scientific journal articles.

The report begins with a general description of some basic concepts involved in forensic seismology in order to familiarize readers with some essential background information. Later chapters explain the University of Toronto team's research objectives and accomplishments since the middle of the 1980s. This work has benefitted greatly from close co-operation with seismic experts from the Geological Survey of Canada.

Chapter 2: Verification

The underlying rationale for reaching an arms control agreement is simple: by virtue of being similarly restrained in weapons testing or deployment, all assenting states expect to gain national security benefits. The actual realization of the anticipated benefits depends on each signatory being in compliance with the terms of the agreement. Since treaty violations by even one signatory could threaten the national security of others, a demonstrable capability for monitoring treaty compliance and detecting violations, if they occur, becomes vitally important.

At present, and for the conceivable future, it is not practically possible to detect with a high level of confidence a very small underground nuclear explosion that takes place at an arbitrary location away from declared test sites. This would be especially true for a test which employs a deliberate evasion scheme, such as seismic decoupling — that is, the use of a cavity to achieve a reduction in strength of the seismic signals leaving the source region.

On the other hand, it is important to consider the military significance of nuclear tests at very low yields. The most crucial part of a modern thermonuclear warhead is called the primary, or fission trigger. Most primaries have yields between 5 and 15 kilotons. The threshold for the physical processes that make small primaries possible (boosting) is about one kiloton or a bit larger. It is generally believed that nuclear testing at a yield level much below one kiloton is not militarily significant.

Verification serves three principal purposes: a) confidence building; b) detection of treaty violation; and c) deterrence to potential treaty violation. Deterrence can result because a small (e.g. 0.5 kiloton) clandestine nuclear test *may* be detected and identified. Moreover, the chances of getting caught cheating increase with the explosion yield.

Nevertheless, because it is not possible to detect and identify all nuclear tests using forensic seismology, views on what constitutes adequate and effective verification differ. In large measure, the desired degree of confidence in verifying compliance with a low threshold test ban depends on one's perception of whether the benefits of an agreement outweigh the potential risks of treaty violation by the other signatories.

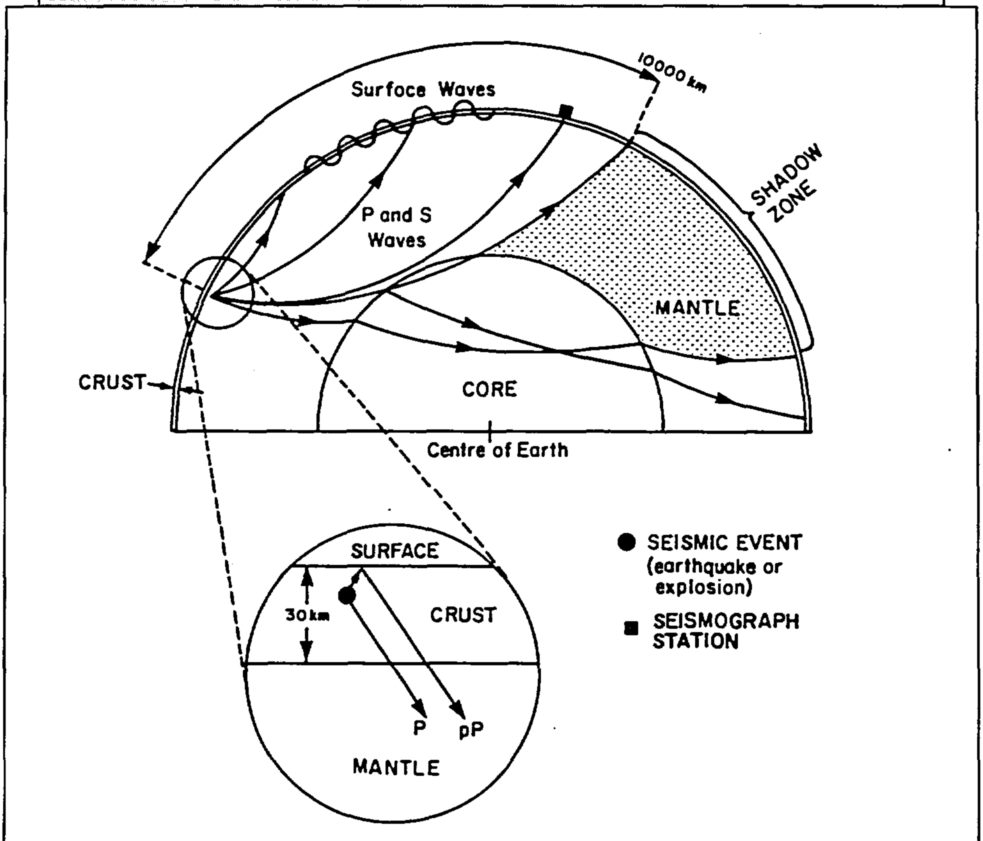
Though they provide the primary means of test ban treaty verification, seismic methods can be made more effective when supplemented by treaty provisions for on-site inspections and the use of "national technical means" (NTM). Thus, a package of mutually reinforcing monitoring methodologies —

seismic as well as non-seismic — will likely constitute the most effective verification approach for nuclear test bans.

Chapter 3: Principal Types of Seismic Waves

The explosive force of an underground nuclear detonation produces seismic waves which travel through the Earth. The outward pushing pressure from an underground explosion favours an efficient generation of compressional waves, or P waves. The "P" is from the word primary because it is the first among an assortment of waves to arrive at a seismograph. One of two types of body waves, the P wave propagates through the deep interior of the Earth. A P wave can reach a seismic sensor 10,000 km distant in about 13 minutes.

Figure 1: Body Wave and Surface Wave Paths in the Earth



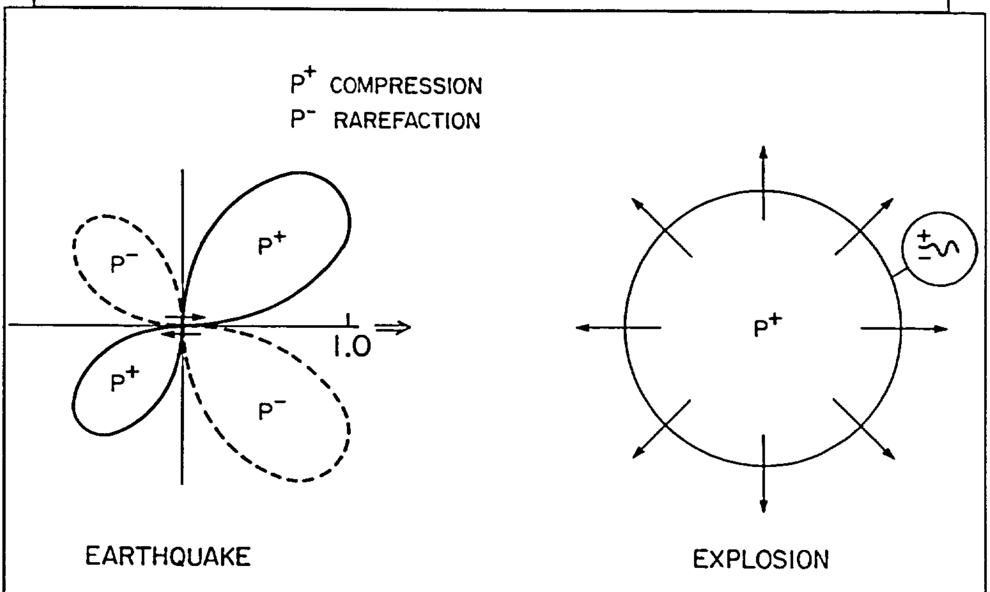
This schematic is taken from the brochure *Yellowknife Seismological Array*, Ottawa: Energy, Mines and Resources Canada, 1989.

An earthquake occurs when one fault block slips past another along a ruptured fault plane. The shearing process between the two fault blocks makes it an efficient source of shear waves, the second type of body waves. The S, or secondary, wave travels more slowly than the P wave, taking nearly twice as long to cover the same distance.

In addition to these body waves, there are also surface waves. The surface waves have longer periods and slower speeds than the body waves and propagate near the surface of the Earth. Figure 1 is a schematic diagram showing the paths taken by body and surface waves. The enlarged circle at the bottom shows a surface-reflected wave called pP phase. The importance of this latter seismic signal for test ban treaty monitoring will be discussed later.

The size of a seismic event is most frequently described by its magnitudes. The two most commonly used magnitudes are: a) m_b, or body wave magnitude, which is based on observed body wave amplitude measured near 1-sec period and corrected for the propagation distance; and b) M_S, or surface wave magnitude, which is based on observed surface wave amplitude measured near 20-sec period and corrected for the propagation distance.

Figure 2: Earthquake Radiation Pattern (left) and Explosion Radiation Pattern (right)



The plus sign indicates compression (pushing) and the minus sign, rarefaction (pulling). The arrow points in the direction of the fault rupture propagation.

The amplitudes of a given type of seismic wave leaving the source region may depend on the wave's direction, and this directional dependence of the seismic amplitudes is called radiation pattern. Figure 2 illustrates the idealized P wave radiation patterns of an earthquake and of an explosion. The earthquake radiation pattern features four lobes whose quadrantal orientations are determined by the direction of the fault slip. The difference in size among the lobes arises from the fault rupture propagation, as indicated by the arrow. The solid lines indicate compressional (pushing) first motion; the dashed lines indicate rarefactional (pulling) first motion. In contrast, the P waves leaving an idealized explosion source have the same amplitude in all directions, and they all have compressional first motion.

The generation of seismic waves is a complex physical phenomenon, but some simple generalizations are still possible. Seismic waves span a broad gamut of oscillation frequency. The efficiency with which low frequency (long-period) waves are produced increases with the seismic source size. A recorded seismic signal is made up of oscillatory motions of many different periods. The amplitude associated with each period may be determined using well established signal processing techniques. Two signals are said to differ in frequency content (or spectral make-up) if one is made up predominantly of low frequency (long-period) oscillations and the other of high frequency (short-period) oscillations.

Earthquakes involve motions between large rock blocks, whereas explosions are small, intense sources of short time duration. The fundamental source differences between earthquakes and explosions are manifested in the characteristics of the seismic waves they produce. Typically, explosion generated P waves feature larger, more impulsive beginnings than do their earthquake counterparts. For similar P wave strength (as measured in terms of body wave magnitude m_b, for example), the earthquakes tend to produce stronger long-period (low frequency) surface waves, and therefore larger surface wave magnitudes M_S. On a more subtle level, the spectral make-up of the seismic signals are different between the two source types, with the explosion generated ones usually showing relative enrichment towards higher frequencies. The analogy with people is that the particular vocal spectral composition makes each person's voice distinct from all others. In other words, explosions tend to have a higher "pitch" than do earthquakes.

Chapter 4: Basic Tasks in Seismic Monitoring

Modern sensors, such as those deployed at the recently refurbished Yellowknife Seismic Array in Canada's Northwest Territories, are extremely sophisticated and sensitive. They are able to accurately reconstruct the continuous, three-dimensional ground motions at the recording site resulting from the arrival of seismic waves from a distant source of tremor. However, the waves, which are already weakened during their long passage, are not recorded without some undesirable companions: locally and regionally generated background noise due to atmospheric perturbations, ocean waves, vehicular traffic, construction and mining activities, and other man-made or natural causes. The relative ratio between the signal strength and that of this ambient noise is called the signal-to-noise ratio. Noise reduction can be achieved by prudent site selection for the monitoring sensors; special design of the seismic array configuration; and, in some places, by installing the sensors in deep bore holes well below the surface of the Earth. A small seismic signal from a distant, low yield underground nuclear explosion may be clearly recognized and analyzed if the recording site noise level is sufficiently low.

Shown in Figure 5a is the cruciform-configured Yellowknife Seismic Array (YKA) — a modernized listening post with an enviable recording history spanning nearly three decades. Because it is within 10,000 km of most of the present underground nuclear test sites in the world, the YKA is strategically located (Figure 5b). The dots in Figure 5a are short-period stations unless otherwise specified; BB and HF are acronyms for the broadband and high frequency stations, respectively. The broadband sensors are exquisite instruments requiring a strictly regulated temperature and pressure environment. To achieve the desired recording environment, the vaults housing these instruments are located in horizontal tunnels dug 10 m into a granite cliff and insulated by two protective doors.

Seismic monitoring consists of four basic tasks: a) event detection; b) epicentral location; c) seismic source identification; and d) yield estimation, in the case of an explosion.

Event Detection

When monitoring seismic activities, the first step is detection — the process of confirming that a seismic event (whether it be an earthquake, nuclear explosion, chemical explosion, volcanic eruption, etc.) has taken place. Detection capability is affected by such factors as the type of seismic stations deployed, the spatial distribution and coverage density of the station network, the ambient background noise, and the tectonic environment in which the network is located.

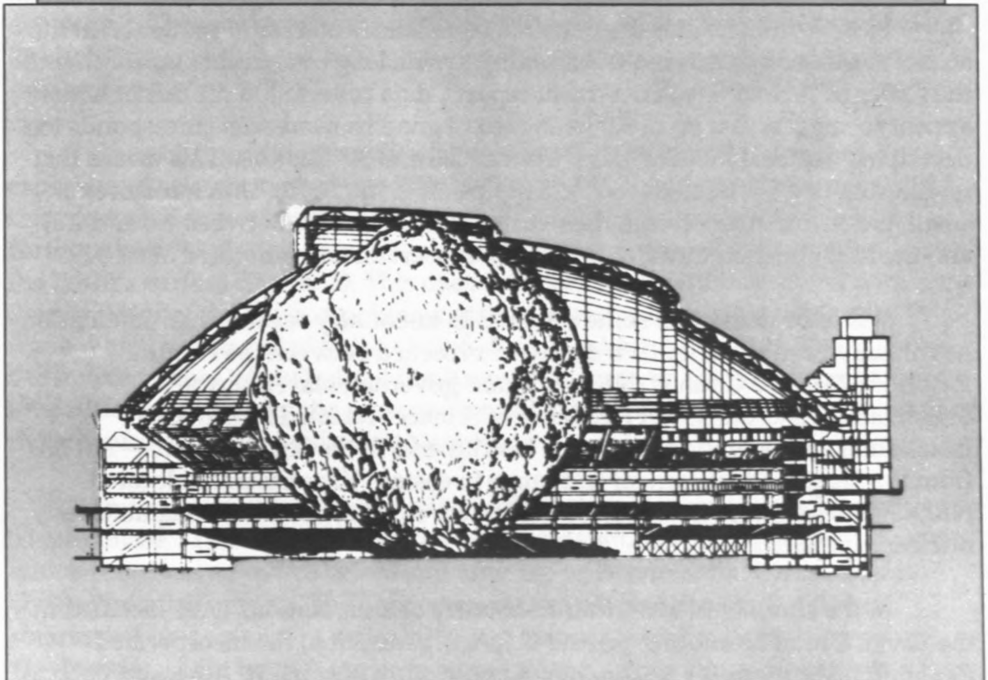
If an underground nuclear explosion takes place in a cavity with a radius above a certain minimum value for a given yield level — a known evasion scheme called seismic decoupling — then noticeably less energy is transmitted, or "coupled", to the surrounding rock. In this case, the explosion will appear to be smaller than it actually is, making detection more difficult. The volume of the cavity required to achieve the desired decoupling increases with the explosion yield[1]. The largest cavities that have been constructed in hard rocks are small compared with the corresponding ones in salt.

There is a widespread agreement among forensic seismologists that the existing technology probably permits the construction of cavities of the size and strength required for repeat clandestine nuclear testing of nuclear weapons of up to 1 or 2 kilotons in yield. The diameter of a cavity in salt to muffle a 5 kiloton explosion is at least 86 m, approaching the height of the *Sky Dome*, a new sports stadium in Toronto (Figure 3). Massive excavations required for decoupling larger nuclear tests would be both costly and technologically difficult, especially when the need for concealment of such activities is taken into consideration. The clandestine construction of a stable cavity sufficiently large to muffle a 10 kiloton explosion is not feasible[2]. Even if the cavity construction is successful, repeat clandestine testings of a few kilotons or more in a fixed cavity carry a high likelihood of being detected and well located, attracting unwanted attention from a monitoring party.

For historical reasons, the Soviet Union has been extensively studied in the West for assessing the future seismic monitoring requirements for that country. The U.S.S.R. has a landmass much different from that of the Western U.S.A. where the Nevada Test Site is located. While verification of treaty compliance today requires a global perspective to seismic monitoring that goes well beyond the national boundaries of the two superpowers, the Soviet Union serves as a convenient model for discussion purposes.

Experience gained by the U.S.A. and a number of other countries suggests that a seismic network of stations located entirely outside of the Soviet Union would be able to detect well coupled explosions with m_b as low as 3.5 anywhere within that country[3]. The associated source *identification* threshold is m_b 4.0, which corresponds to a well-coupled explosion with a yield of 1 kiloton. With an additional in-country, 25-station monitoring network, the detection threshold lies between m_b 2.0 to 2.5. The associated source identification threshold can be at least as low as m_b 3.5, depending on the way treaty provisions are negotiated to handle chemical explosions. Compared with the 0.5 m_b gap between the detection and identification thresholds for teleseismic events, the corresponding gap for small regional events is conspicuously larger.

Figure 3: Cavity Decoupling



With a minimum diameter of 86 m, a hypothetical spherical cavity constructed in salt to muffle a 5 kiloton explosion is contrasted here with the *Sky Dome*, a new sports stadium and Toronto landmark.

One important reason for the latter's enlarged gap between the detection threshold and identification threshold is that the regionally recorded signals from small events, being made up mostly of high frequency oscillations, are much more susceptible to frequency-dependent signal distortions occurring near the recording stations. Because the Earth's lateral heterogeneity, which causes the site effects, is more pronounced near its surface, the characteristics of the high frequency regional signals are much more variable among the recording stations than their lower frequency teleseismic counterparts. Consequently, large signal amplitude serves to ensure event detection, but not necessarily source identification, unless a fairly large number of stations record a given event so that the site effects can be averaged out.

As an alternative to averaging out the site-effect differences using a large number of recording stations, these differences could be suppressed by means of network calibration. A direct consequence of the network calibration is a reduction in the number of recording stations required per event for reliable source identification and, by implication, a reduction in the source identification threshold.

Now let us consider the potential significance of a slight reduction in the source identification threshold pertaining to small regional events. According to the Office of Technology Assessment report[4], data collected in the Soviet Union appear to suggest that m_b of 3.0 in an area of good transmission corresponds to a decoupled explosion with a yield between 2.6 and 3.8 kilotons. This means that monitoring of a 5 kiloton decoupled explosion in the Soviet Union requires a small, partial closure between the detection threshold (m_b between 2.0 and 2.5) and the identification threshold, which is conservatively estimated at m_b 3.5.

It is to be noted that some progress in in-country seismic instrumentation has already been made. A 1986 agreement reached between the Natural Resources Defense Council (NRDC), a non-governmental American organization, and the Soviet Academy of Sciences resulted in temporary installation and operation of seismic instruments in the Soviet Union — not far from the Shagan River nuclear test range in eastern Kazakhstan. Relocated NRDC stations were subsequently permitted, in 1988, to record Shagan River nuclear explosions at regional distances.

In the summer of 1988, four in-country seismic stations were installed in the Soviet Union by another private U.S.A. organization, the Incorporated Research Institutions for Seismology, a consortium of some 70 American colleges, institutes and universities. These installations, also permitted under an agreement with the Soviet Academy of Sciences, were in place in time to record a historical seismic event in the Soviet Union — the Joint Verification Experiment of September 14, 1988, which was conducted by the U.S.S.R. and the U.S.A. The current plans by the United States Geological Survey envisage the installation of as many as 25 in-country stations within the Soviet Union.

Event Location

Following detection, it is necessary to determine where the seismic source was located. Suppose several stations record P waves coming from a given event. At each station, the P wave arrival time depends on the path length connecting the source with a given station. The arrival time differences among the recording stations provide the necessary information for a seismic analyst to locate the source, generally within 10 to 30 km accuracy for many modern networks conducting routine monitoring of earthquake activities. If the stations also record other wave types of varying propagation speeds, the location accuracy would be better, as would also be the case if the station coverage density is increased.

A very important piece of information about a seismic source is its focal depth below the Earth's surface. This is so because seismic sources much deeper than a few kilometres are unlikely to be clandestine underground nuclear explosions. The enormous costs aside, drilling operations required for such deep test holes are massive and difficult to evade detection from reconnaissance satellites and other NTM.

One of the most telling clues to the source depth may be found by an experienced seismic analyst in subtle changes of the oscillatory behaviour of the seismic record soon after the first-arriving P wave. A body wave leaving an earthquake or explosion source along a fairly steep, upward path is reflected at the Earth's surface (Figure 1). This once-reflected wave will then travel within the deep interior of the Earth, reaching a distant station a short time behind the P wave which has travelled to the station directly without the short detour above the source region. When both of these waves are seen on the station record, the time difference between the two can be used to determine accurately the depth of the seismic source below the Earth's surface.

Experts give this class of surface-reflected body waves a special name: "depth phase". The most commonly observed depth phase is pP, a seismic wave which travels as a P wave before and after the reflection at the Earth's surface above the source region. The time taken for the pP phase to reach a distant station differs from that of a direct P by an amount which roughly corresponds to the duration spent by the former to complete the detour above the seismic source.

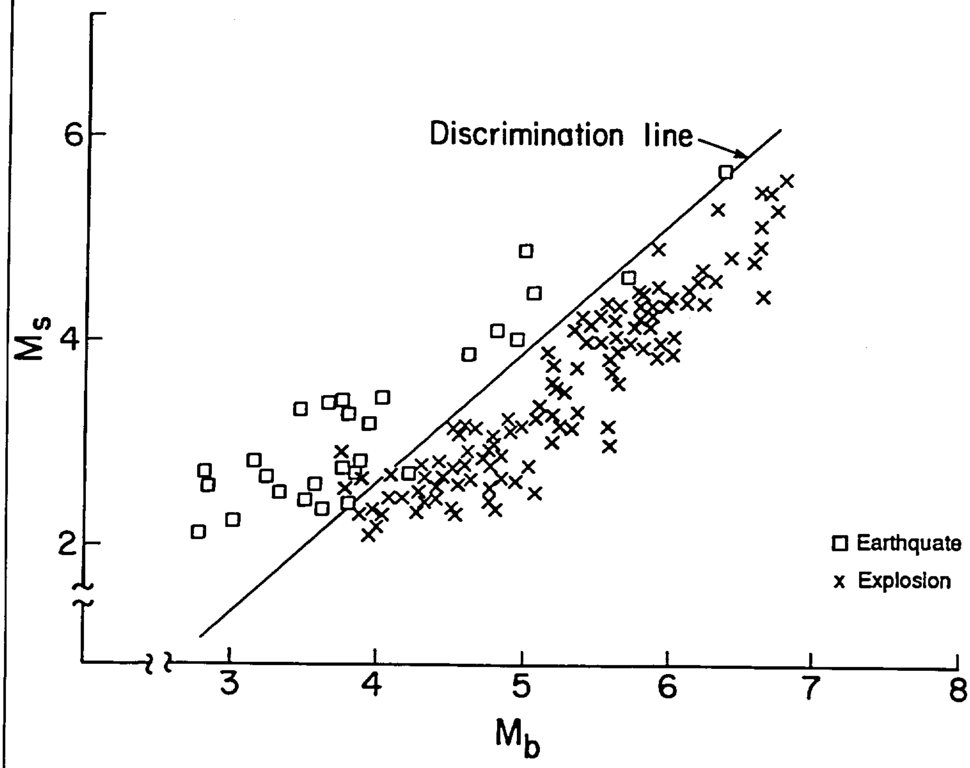
The depth phases are elusive creatures, however. For a given seismic event, the depth phases may show up at some stations but not at others. Or they may not show up at all, especially when the sources are shallow, within the uppermost part of the Earth's crust. In some instances, highly sophisticated signal processing may succeed in unmasking their presence. Examples of a successful attempt to unmask hidden pP waves will be shown in Chapter 6.

Source Identification

To verify compliance with a nuclear test ban treaty, it is necessary to identify the nature of the seismic events that one has detected and located. We have already discussed the source differences between earthquakes and explosions. Large earthquakes are rare, and the source identification for these is straightforward. The most powerful earthquake/explosion discrimination method is based on a pair of measured values: body wave magnitude m_b and surface wave magnitude M_S, which we discussed earlier in Chapter 3. At a given m_b value, earthquakes have larger M_S magnitudes than do nuclear explosions. As the source strength decreases, the source identification becomes progressively more cumbersome and less straightforward. Figure 4 shows a plot of observed

m_b and M_s values for underground explosions at the Nevada Test Site and for Western U.S.A. earthquakes. Note that small explosions with m_b near 4.0 and less tend to cross the "discrimination line" and mix with small earthquakes.

Figure 4: Plot of m_b Versus M_s



Modified from OTA Report, May 1988. Original source: S.R. Taylor, M.D. Denny, and E.S. Vergino, "m_b: M_s Discrimination of NTS and Western United States Earthquakes: A Progress Report", Lawrence Livermore National Laboratory, January 1986.

Annually, there are between 6,000 and 9,000 earthquakes occurring globally with m_b above 4.0, which is approximately the size of a 1 kiloton underground nuclear explosion detonated in hard rock (granite) environment. When earthquakes with m_b between 3.5 and 4.0 are added, the total number nearly triples. An m_b of 3.5 corresponds to what many experts regard as a conservative (too high) source identification threshold in the U.S.S.R. when in-country and external seismic stations are both available[5].

The sheer number of seismic events aside, some small detected events may be poorly recorded, rendering accurate epicentral and focal depth determinations impossible without strenuous effort. Generally speaking, source identification requires a higher signal-to-noise ratio (S/N) (cleaner signal quality) than epicentral location, which in turn requires a higher S/N than the mere event detection. Past experience with teleseismic signals suggests that, the source identification threshold is about 0.5 magnitude unit larger than the detection threshold. The threshold gap may be larger than 0.5 for regionally recorded events with m_b less than 3.5.

The most efficient way of handling such a large number of events is to begin with a winnowing process. About 90% can be identified as earthquakes simply because their focal depths are too large, or their epicentral locations are deemed too implausible, or both, for underground nuclear tests. The location information can be used to weed out a large fraction of chemical explosions for mining and construction, rockbursts, vehicular traffic, and other sources. Treaty provisions requiring advance notification of these man-made activities could help make the winnowing process even more efficient.

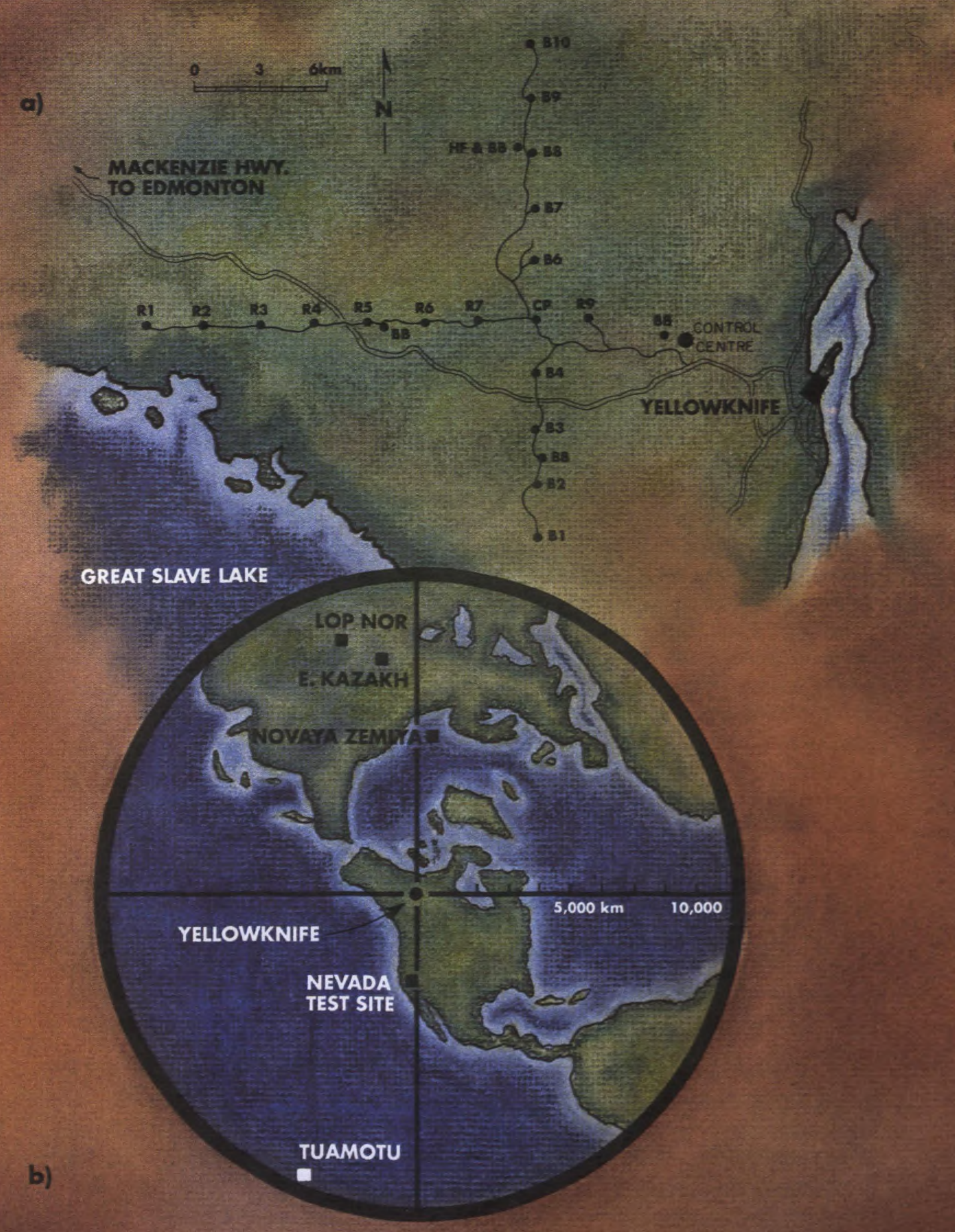
The identification of the remaining events, still numbering in the hundreds per year, if not in the thousands, is a challenging task. Moderate-sized (m_b in the vicinity of 4.0) and small earthquakes are poor generators of long-period surface waves. Even less surface waves are produced by underground explosions in this magnitude range. As a result, the m_b versus M_s discrimination method which works so effectively for larger events ceases to be useful. Source identification based on observed differences in spectral make-up at high frequencies (greater than 1 cycle per second) between earthquakes and explosions is a topic of active research.

Explosion Yield Estimation

If all nuclear tests are to be banned, as under a CTBT, there will be no need for yield estimation. At present, there are still differing opinions about the verifiability of militarily significant clandestine tests which are carried out using elaborate evasion schemes. This grey area covers clandestine nuclear tests with yields of several kilotons. As a result, a low yield threshold test ban treaty (LYTTBT) may appear to be a more widely acceptable option in the near future.

For any threshold test ban treaty (TTBT), including the 1974 Treaty signed by the U.S.A. and the U.S.S.R. limiting the maximum allowable yield to 150 kilotons, it is necessary to measure nuclear explosion yields in order to determine if they stay below the threshold permitted by the treaty. Seismic yield estimation is accomplished by establishing an empirical (seismic) magnitude versus yield relationship using explosions of known yields. Once established, such a

Figure 5 The Yellowknife Seismic Array



c)

Photos courtesy Geological Survey of Canada

Refurbished in 1989 at a cost of $3.5 million, the Yellowknife Seismic Array (YKA) is a key listening post, sensing vibrations caused by underground nuclear explosions and other seismic sources. The updated YKA preserves the cruciform layout of the original teleseismic array established in 1962 (a). The broadband (BB) and high frequency (HF) instruments are three-component new additions installed during the refurbishment. The remaining instruments – 18 in total – are short-period vertical-component stations, modernized to gain enhanced reliability. All are digital stations relaying their data by radio to the Control Centre (d) and on to the Geological Survey of Canada in Ottawa by Anik satellite.

d)

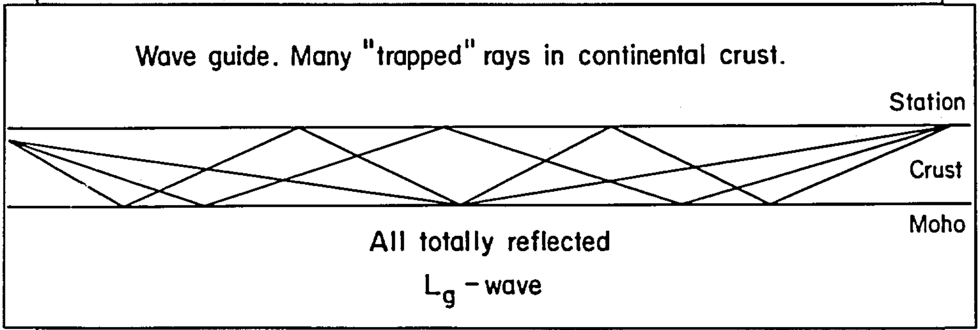
Strategically located to place most major test sites within efficient teleseismic recording distance (3,000 to 10,000 km), the YKA registers seismic signals from the most distant test site – French Tuamotu – in less than 13 minutes (b).

While the remote location of the YKA – away from coastlines, urban areas and other sources of seismic noise – facilitates acquisition of clearer seismic signals for forensic analysis, the difficult nature of the local terrain imposes some unusual demands, such as the specialized vehicles needed to move between the stations (c).

relationship is then used to determine, from the measured seismic magnitudes, the yields of the explosions being monitored.

The Nevada Test Site in the Western United States is located in a region whose tectonic features and subsurface temperature are significantly affected by the ongoing motions between the North American and the Pacific tectonic plates. Hot and more absorbent of vibrational energy, the rock deep beneath the Nevada Test Site is an inefficient medium for seismic wave propagation. In contrast, the Soviet test sites are located in geologically old, stable regions — like the Canadian Shield. Because the rocks below these regions are cold and more solid, they are efficient media for seismic wave propagation.

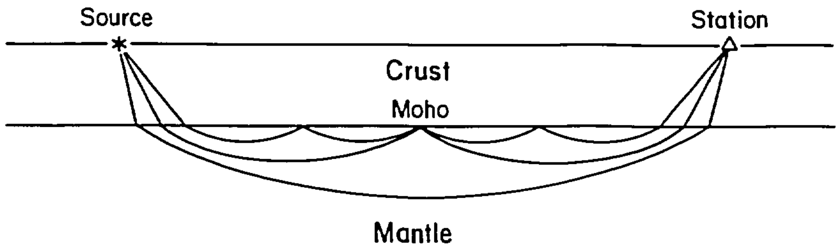
Figure 6: Propagation of L_g Wave in Earth's Crustal Wave Guide



Taken from OTA Report, May 1988.

When an earthquake or explosion takes place, several types of seismic signals are generated. For monitoring the compliance with a CTBT or a LYTTBT, the two most important information laden seismic signals are P_n and L_g. The L_g, consisting of many "trapped" rays in continental crust some 30 km thick, propagates in the wave guide at a velocity of around 3.5 km per second. Figure 6 is a schematic drawing of a few family members of the trapped rays which make up the L_g wave. The P_n, on the other hand, is made up of a series of diving waves bent by the velocity gradient and internally reflected at the underside of the Moho discontinuity that separates the crust from the underlying mantle[6]. The upper mantle velocity gradient, which controls how fast the P_n energy spreads out geometrically, varies from region to region. Figure 7 represents a schematic drawing of a few family members of such diving waves[7]. The manner in which the multiply bounced rays converge is known as the "whispering gallery" effect.

Figure 7: *P_n Phase as a Superposition of "Diving Waves"*



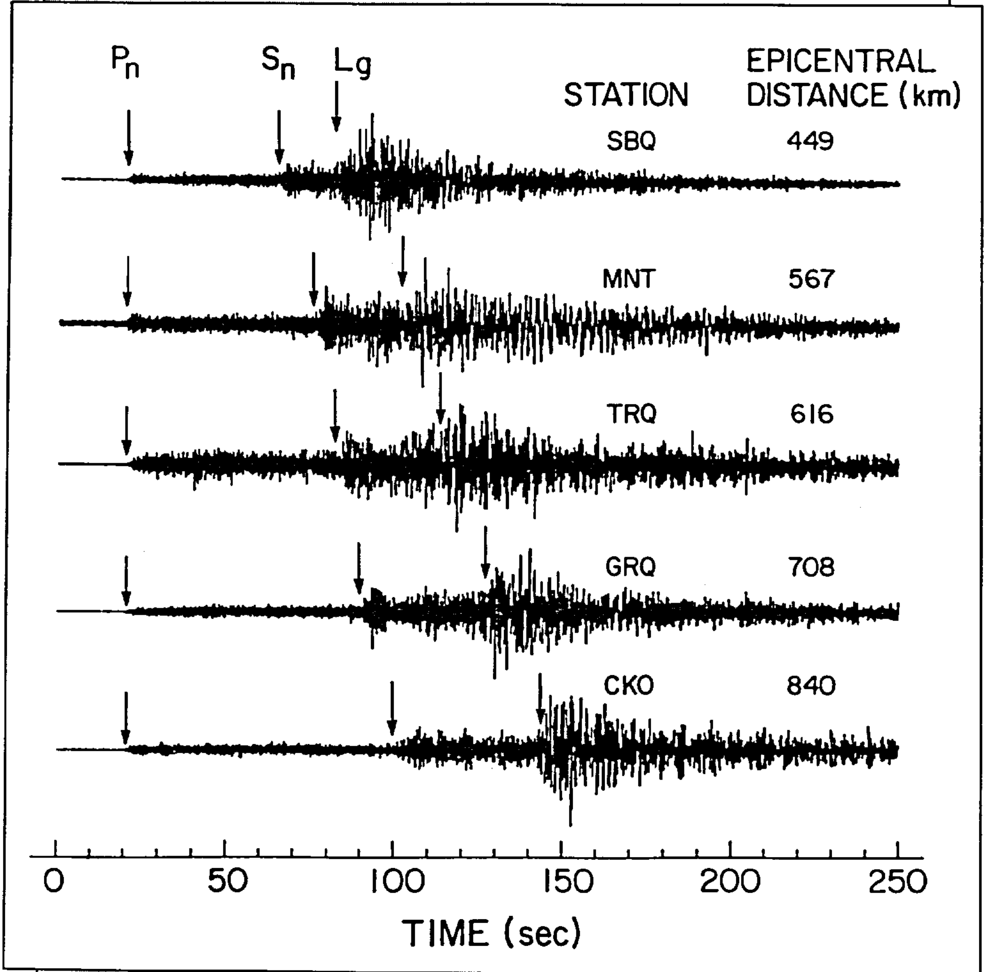
Modified from Chun *et al.*, 1991a. The "whispering gallery" effect (see text) differs from region to region because of the differences in velocity gradient which controls the curvatures of the diving waves.

Figure 8 shows typical examples of regional earthquake recordings from Eastern Canada Telemetered Network stations[8]. In each record, three types of seismic signals are visible. P_n is the earliest arriving signal, and L_g the latest. The beginning of each signal is indicated by an arrow. Overall, the records bear a remarkable resemblance to their counterparts from Eastern Kazakhstan[9].

Between the Soviet and American test sites, the P_n and L_g transmission efficiencies differ greatly. Consequently, at a fixed yield level, a Soviet explosion will register a larger magnitude than a Nevada Test Site explosion. Conversely, for a given observed magnitude value, a U.S.A. nuclear test will have a larger yield than does a Soviet test.

One other important factor which affects the magnitude versus yield relationship is the manner in which the explosive energy is coupled to the Earth. This energy coupling depends on the type of rock in which the nuclear test device is detonated. Proper accounting for the differences in energy coupling and wave attenuation among the test sites can be achieved through test site calibration using nuclear devices of known yields.

Figure 8: Examples of Regional Recordings of Moderate-sized Earthquakes



These seismograms, collected from Eastern Canada Telemetered Network stations, bear close resemblance in overall appearance to their counterparts from Eastern Kazakhstan.

Chapter 5: Seismic Monitoring, the Earth and the Telephone System

In principle, the seismic detection and location thresholds within the territory of a country being monitored can be lowered to any desired level if enough in-country seismic stations are deployed. From the technical standpoint, the more important aspects to be addressed are the source identification and yield estimation capabilities which are attainable using a realistic network of in-country monitoring stations. The word *realistic* pertains to the financial costs and intrusiveness associated with the monitoring activities. Reliable source identification and yield estimation depend critically on the ability to make stable measurements of not only the ground motion amplitudes but also the exact spectral composition, especially of P_n and L_g waves.

If the Earth were perfectly quiet and were made of homogeneous rock layers, the amplitude of the seismic waves would decay smoothly and predictably with distance away from a seismic source. By extrapolating the measured ground motion amplitudes back to the source point, one obtains a precise estimate of the source strength. In this case, if plotted on a chart, the observed magnitude against known yield points would fall on a smooth curve with no scatter and the same curve can be used anywhere in the world. Yield estimation on this hypothetical Earth would thus be easy. For a given observed magnitude m_b, for example, one simply reads the corresponding yield value from the curve.

Seismic waves are composed of oscillatory motions of many different periods. For a given seismic record, the oscillation amplitude associated with each period can be measured using well established techniques. The amplitude variation with wave period is called "spectral make-up" or "frequency content". The spectral methods for identifying seismic sources require that we be capable of finding out from the recorded seismic data the spectral make-ups of the seismic waves leaving the source regions — before signal-distorting path and site effects have taken place. In our daily life, we routinely differentiate people's voices and sounds from various musical instruments by their acoustic spectral make-up; we can even detect a speaker's emotional variation by noting subtle changes in his/her "pitch". Difficulties arise when a speaker's voice is heard through a low-fidelity electronic audio system. In this case, the acoustic composition of the voice can be so distorted that one is no longer able to recognize the speaker's distinct pitch — no matter how loud the voice is amplified.

For the hypothetical Earth described above and for a given type of seismic signal, the manner in which the signal is continuously distorted along a wave path can be calculated or measured experimentally. Seismologists are good at doing both. Knowing how a signal is systematically distorted enables them to make corrections for the signal distortions which have taken place for a given seismic signal between an explosion (or earthquake) source and the recording stations.

The real Earth is neither perfectly quiet nor made of homogeneous rock layers. Exposed rock outcrops differ in their elastic properties, and hence their "springiness". In fact, the uppermost crust of the Earth varies strongly from place to place. The shallow geological structure beneath a seismic recording station, with its particular elastic properties, acts much like a low-fidelity audio system with an unknown amplification factor. It gives rise to near-station signal distortion and amplification (or deamplification) phenomena which are collectively called "site effects." While the modern seismic recording instruments are extremely sophisticated and reliable, they can pick up the seismic signals impinging from below only after the latter have been subjected to signal-distorting station site effects.

The existence of the site effects poses a fundamental difficulty for forensic seismologists. Without an effective method to correct for the site effects, it is not possible to obtain reliable information on the attenuation characteristics of seismic signals along their wave paths. And without an accurate knowledge of the wave attenuation characteristics, it is not possible to make accurate frequency-dependent corrections for the seismic amplitude reduction between the source and the recording stations located at various epicentral distances. Consequently, the explosion yield and the source type determinations can be quite uncertain.

The yield scatter among results from different stations can be as large as a factor of ten. Returning to Figure 4, we see a large magnitude scatter that would translate into a large yield uncertainty. The scatter is typical of such plots. Largely because of site-dependent modifications in spectral make-up, a given seismic event may appear to be an earthquake at some stations but not so at others. For a large seismic event that is well recorded at many stations, the individual station results can be averaged and reliable source inferences made.

The task of monitoring the compliance with a LYTTBT or CTBT with a limited number of monitoring stations is quite another matter, unless all signatory nations agree to and abide by a treaty provision allowing tests to be conducted only in strictly designated test areas. If the explosion sites are fixed and known, it turns out one can train one's fixed in-country "ears" (seismic listening posts) to recognize the explosion sources down to a yield level possibly as small as a fraction of a kiloton. What are needed for such a scenario are a series of calibration nuclear tests which are carried out under close technical surveillance by the monitoring parties.

Recent research carried out by Norwegian and American seismologists has shown that very accurate yield estimation can be made using L_g wave recordings if the source/station configuration is kept fixed. To demonstrate this, they used Eastern Kazakhstan nuclear explosions data recorded at fixed stations in the Soviet Union and China — at epicentral distances ranging up to 3,000 km — and showed that it is indeed possible to obtain extremely stable measurements of the explosion source sizes down to one kiloton and less.

The signal recognition and yield estimation processes in this case are akin to getting used to a vintage telephone receiver hooked to a fixed telephone line. Assume, for example, that the voice of a particular speaker is heard repeatedly by a listener in two ways: through the air (the usual way) and through a vintage telephone receiver attached to a fixed telephone line. With enough practice, an attentive listener can learn to recognize that particular voice on the other end of the telephone line, and estimate if the speaker's voice is louder or lower than usual. As long as the net signal modification remains unchanged from one telephone call to the next, it is not necessary to find out how much signal distortion occurs along the telephone line, and how much within the receiver. Note that the "ears" thus calibrated would not work next time if either the telephone line or the receiver is replaced by a totally different one. Here, we equate the signal attenuation and distortion along the telephone line with those along a wave path between a seismic source and a seismographic recording instrument; we equate the signal distortion and amplification/deamplification taking place within the telephone receiver with the site effects due to near-station, shallow geological structures. When monitoring nuclear explosions at a known test site, the path and site effects stay the same. Given a series of calibration explosions of known yield and other pertinent technical details, the monitoring network of stations can be "trained" to perform the desired tasks.

When monitoring is extended to include off-test-site seismic events, the task of verifying the compliance with a LYTTBT unfortunately becomes much more challenging. This is the case because, by severing the particular geological structure beneath a monitoring station from a previously fixed wave path and reattaching it to a new path, the net combined path and site effects are changed, negating empirical experience gained through earlier test-site-specific calibrations.

The technical difficulty here is basic to many branches of geophysics: the problem of isolating the parameter(s) of interest from a host of other interfering ones. A ground motion record represents the combined effects of the seismic source, the Earth attenuation, the station site effects and the recording instrument characteristics, if not also of the ambient noise. In practice, most available sources for seismic parameter determinations are earthquakes. An earthquake is a complex source and it does not radiate seismic energy evenly in all directions or at all frequencies. The problem is compounded by the fact that two different paths of equal length and from the same geological region do not in general share the same attenuation properties. Furthermore, the existing seismic instruments operating around the world today are a mixture whose recording fidelity spans a very broad range indeed. To extract from the seismograms reliable information about the seismic attenuation and the station site effects thus appears to be a formidable task in itself.

Chapter 6: Teleseismic Monitoring Research: A Canadian Stronghold

The Yellowknife Seismic Array: Old and New

Teleseismic monitoring pertains to distances greater than 2,000 to 3,000 km. The Canadian involvement in this field dates back to 1962 when a cluster of seismic stations arranged in a cruciform configuration were installed near Yellowknife, Northwest Territories (Figure 5a). Known as the Yellowknife Seismic Array (YKA), it is one of the few such facilities in the world with a continuous recording history spanning nearly three decades. Its central location with respect to most nuclear testing sites makes the YKA particularly valuable.

External Affairs and International Trade Canada together with Energy, Mines and Resources Canada made possible the refurbishment of the array in 1989, turning it into a state-of-the-art facility for monitoring global seismic activities, both natural and man-made. The refurbished YKA now features three different types of digital recording instruments: a) 18 short-period, vertical-component stations; b) 4 broadband, three-component instruments; and c) 1 high-frequency, three-component instrument sampling at a high, 100 points/sec rate. Data from the YKA have proven extremely valuable in the University of Toronto forensic seismology research described below.

An International Experiment

The YKA has also recently made a significant contribution to an international seismic data exchange experiment conducted by the Geneva-based Conference on Disarmament's Ad Hoc Group of Scientific Experts (GSE). The GSE received a mandate from the Conference on Disarmament in 1976 to undertake the conceptual design of an international seismic data exchange system that would assist in monitoring a test ban treaty and providing the data required for national verification of compliance. Two seismologists from the Geological Survey of EMR — Dr. Peter Basham and Dr. Robert North — represent Canada in the GSE. In 1988, they accepted the role of Coordinator of a major experiment called GSETT-2 (GSE Second Technical Test). GSETT-2 was an experiment designed to test the seismic data exchange concepts in practice using existing or newly installed facilities. It involved 35 countries and 56 seismograph stations, with special processing facilities at experimental international data centres in Australia, Sweden, U.S.S.R. and U.S.A. The final phase of the experiment ran for 42 consecutive days from April 22 to June 2, 1991, detecting and locating between 50 and 100 global seismic events per day. The YKA provided Canada's contribution to this experiment and was consistently among the top three stations in contributing to the detection of seismic events. The evaluation of the results of such technical tests constitutes an important ingredient in the development of a global seismic verification capability.

Teleseismic P Wave Attenuation

The University of Toronto team has recently completed a comprehensive seismic attenuation investigation along the paths connecting the YKA with seven active nuclear test areas. These test areas are: Pahute Mesa and Yucca Flat (both in Nevada), Shagan River and Degelen Mountain (both in Eastern Kazakhstan), Western Kazakhstan, Novaya Zemlya and French Tuamotu.

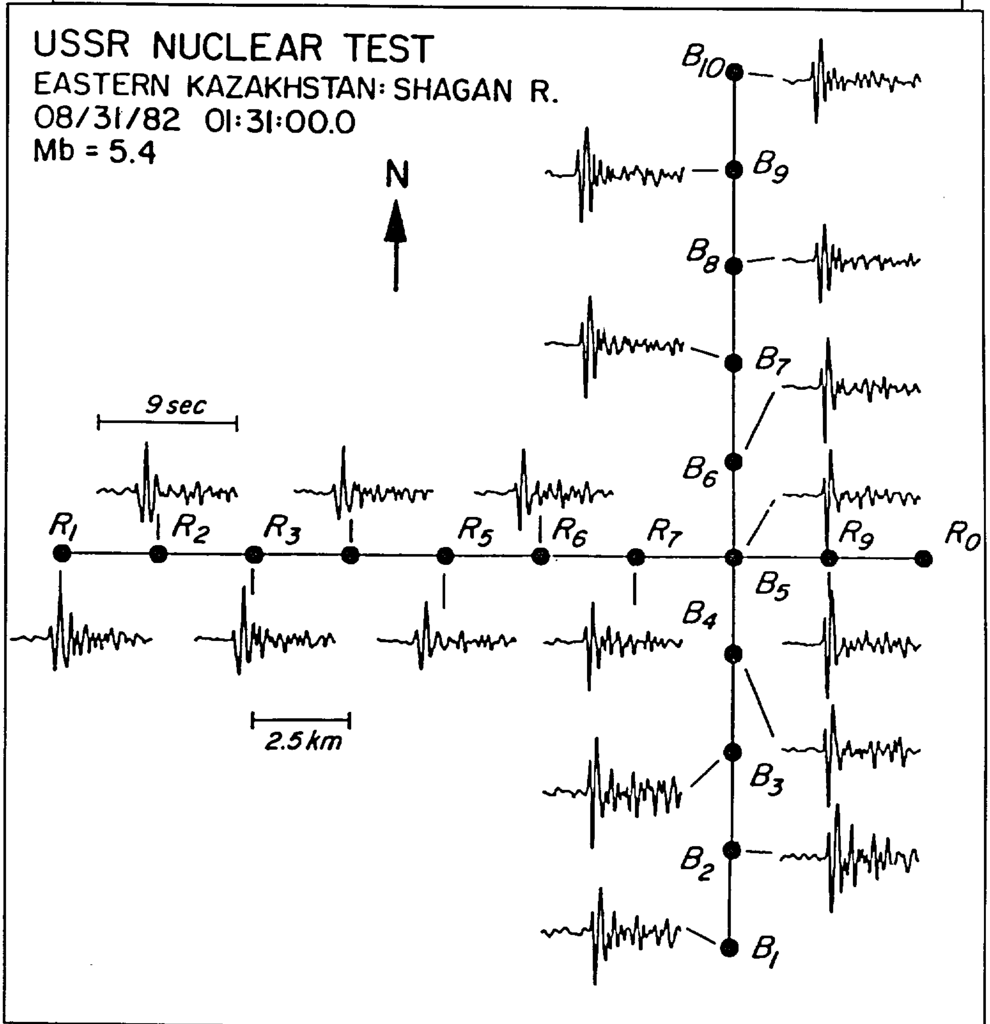
Shown in Figure 9 are YKA recordings of a magnitude 5.4 Eastern Kazakhstan nuclear explosion in 1982. The epicentral distance is about 7,500 km (see Figure 5b). The first sharp "break" (seen as an abrupt upward motion) in each of the 9-sec long record segments indicates the arrival of the direct P wave. The YKA station B_{10} registers the P arrival the earliest and station B_1 the latest, revealing that the epicentral location is essentially due north. The signature and amplitude differences among these records, clearly visible to a trained seismic analyst, manifest the presence of station site effects, which are relatively weak by the normal standards. A University of Toronto team's study based upon more than 600 Yellowknife Seismic Array recordings of known underground nuclear explosions has documented major attenuation differences among these teleseismic paths and their attendant implications in explosion yield estimation error[10].

Unmasking of Depth Phase pP

As was previously stated, the seismic phase pP is important because it provides the crucial source depth information needed to winnow out a large fraction of earthquakes at an early stage of seismic source identification process. Figure 10 shows the vertical-component seismograms obtained at the YKA station B_{10} of five French Tuamotu nuclear explosions[11].

With their m_b values ranging from 5.5 to 5.7, the expected device burial depths are such that the time differences between pP and direct P should stay well below 1 sec — unless the test holes were deliberately dug, at a great cost, to depths well in excess of what were actually needed to prevent radioactive venting. We note in Figure 10 that the first "swing" in each record clearly begins with an upward motion — in accordance with theoretical prediction for an explosive source. Apparently missing in each record is the pP phase which we expect to see shortly following the direct P wave onset (indicated by a short bar).

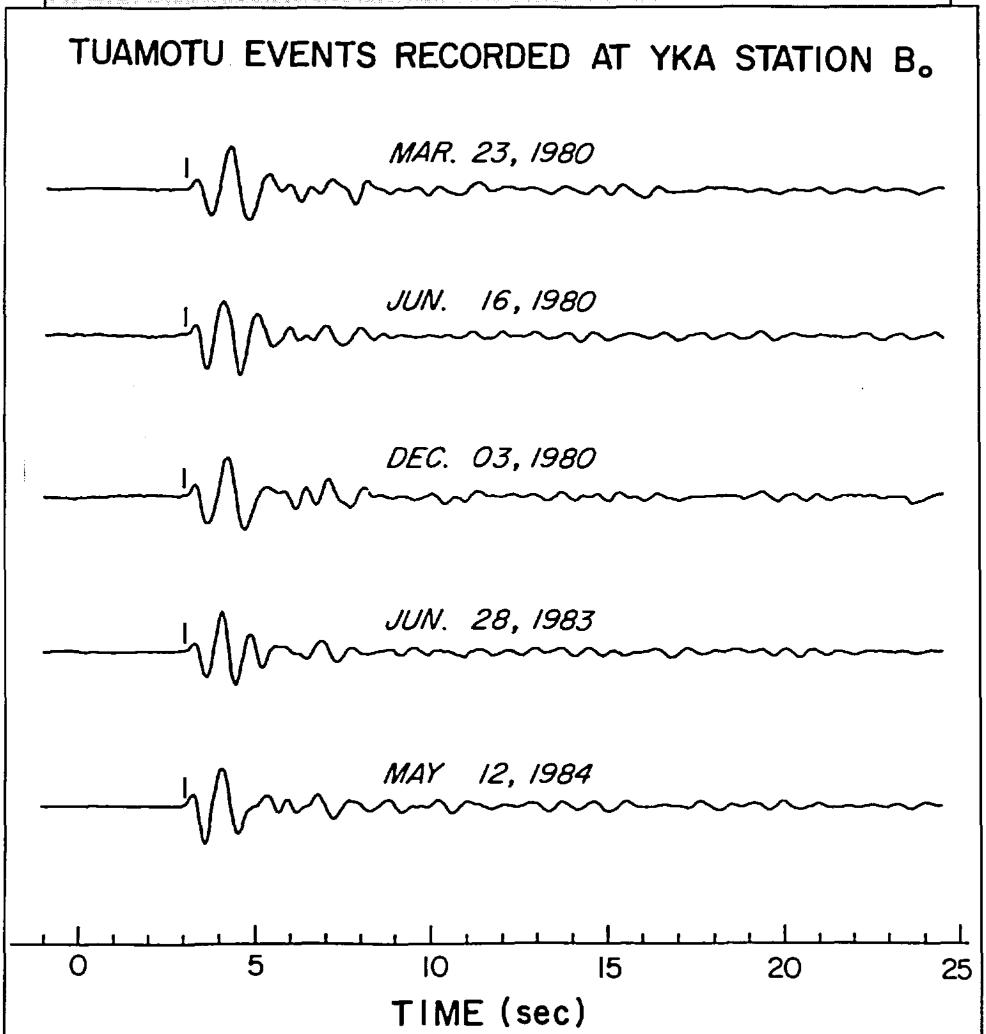
Figure 9: Yellowknife Recordings of an Eastern Kazakhstan Nuclear Explosion



These recordings, each nine seconds long, show large signal amplitudes and low background noise levels.

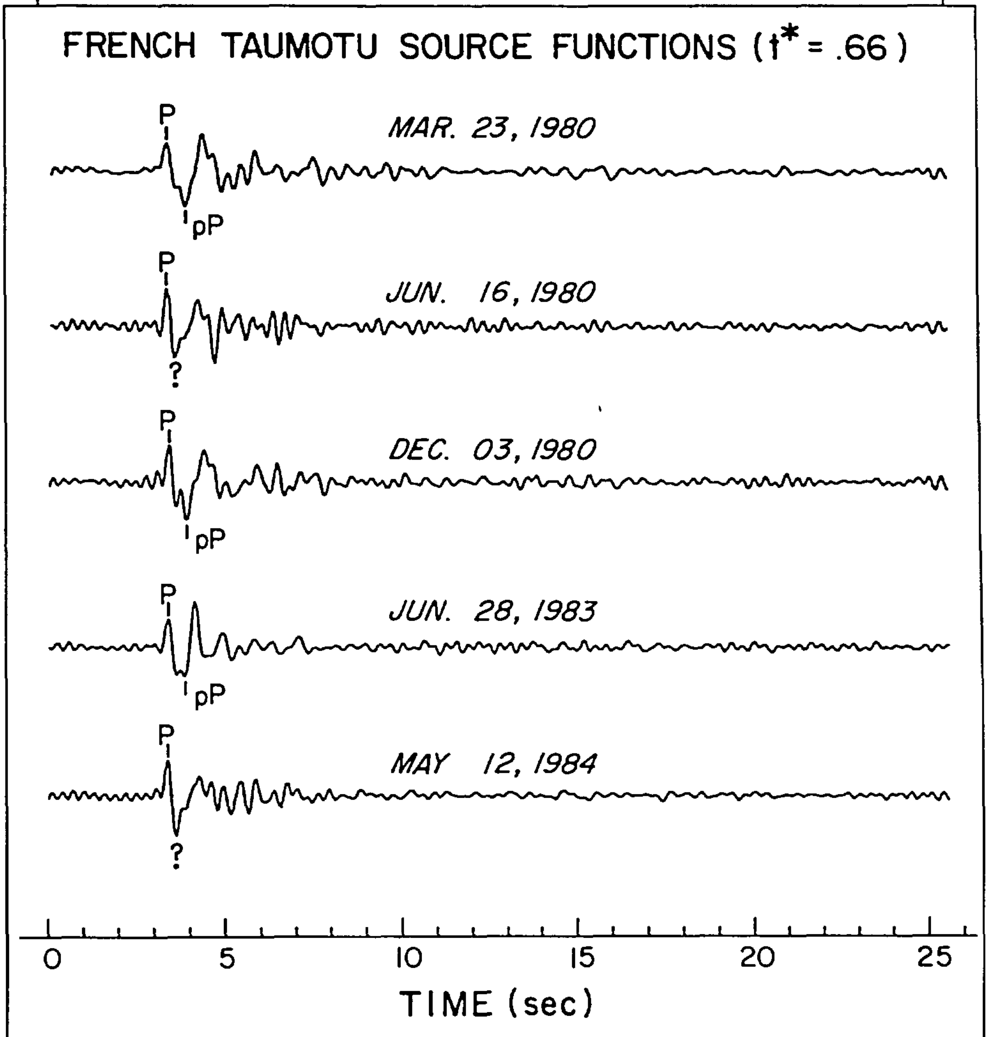
Figure 11 shows the nuclear explosion source functions extracted from the data in Figure 10 using the attenuation results we have obtained[12]. The time separations between the direct P and the pP are about 0.4 second, suggesting that the sources are merely a few hundred metres deep. Critical seismological studies such as this often require a voluminous body of archived nuclear explosion data. Yellowknife is among the very few state-of-the-art seismic arrays in the world having a long data gathering history to meet such a requirement.

Figure 10: Recordings of Five French Tuamotu Nuclear Tests



These recordings are from B_{10}, the northernmost station of the Yellowknife Seismic Array. Short bars point to the P wave onset (arrival) times.

Figure 11: Nuclear Explosion Source Functions for Tuamotu Tests



These functions are extracted from the records shown in Figure 10. A secondary signal pP is seen following shortly after each direct P wave onset time. The time separations suggest that the seismic sources are merely a few hundred meters deep.

Improving Array Location Accuracy

Use of the YKA data, in place of global network data from hundreds of widely distributed stations, enables Canada to gain location information on anomalous teleseismic events within 20 minutes to 1 hour of their occurrences — this might be fast enough so that necessary actions under an international treaty regime could be taken. However, speedy information access gained this way usually comes at a price: a poor location accuracy due to the limited array aperture.

To improve the array location accuracy, the University of Toronto team has launched a research project consisting of two parallel subprojects. The first involves the introduction into wavefield decomposition analysis of a sophisticated signal processing method developed largely by applied mathematicians working outside the field of seismology. Termed "oriented energy approach", our newly developed wavefield decomposition technique analyses the behaviour of seismic waves arriving from distant sources and recorded by the newly installed three-component broadband recording instruments. By keeping track of the array site ground motions in three dimensions and by comparing the recorded waves with predictions based upon known epicentral locations, we can obtain region-specific location corrections for future use.

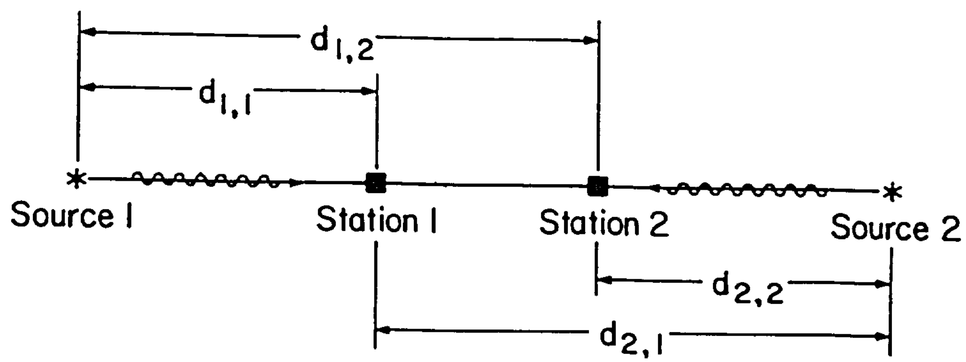
The second subproject takes advantage of YKA's large body of archived vertical-component data from the pre-refurbishment era to investigate the behaviour of seismic wave fronts arriving from distant sources as they sweep across the array site. By noting the speed and the direction of these wave fronts and comparing them with predictions based on known epicentral locations, we can again obtain necessary corrections to improve the array's location capability. Preliminary results from these two separate subprojects are encouraging.

Chapter 7: Close-in Monitoring: Canadian Innovations That Work

Background

The past decade and a half have seen a strong surge of interest in reinvigorating the regional (close-in) seismic verification research in anticipation of a favourable international political atmosphere for the negotiation of treaties that are more stringent than the existing 150 kiloton TTBT. Recent developments conducive to the furtherance of test ban negotiations include the installation of in-country seismic stations in the Soviet Union and the Joint Verification Experiment which involved the detonations of two calibration nuclear explosions — one in Nevada and the other in East Kazakhstan. The University of Toronto's regional forensic research focuses upon path attenuation and site effects of P_n and L_g waves. In the case of P_n wave, we have also carried out studies aimed at gaining insights into the poorly understood behaviour of its propagation mode in the real Earth. Such studies are necessary to remove one of the best known sources of disparity among the published P_n attenuation measurements.

Figure 12: Source-station Congifuration Used in the Reversed Two-station Method



This configuration is in map view. The basic concept of the method is given in the text.

A Novel Technique for Measuring L_g Wave Attenuation

Consider a great-circle path passing through two seismic sources and two seismic stations (Figure 12)[13]. It turns out that the L_g attenuation between the two seismic stations so positioned can be neatly extracted even in the presence of unknown site effects, unknown recording instrument errors and unknown seismic source complications.

The method, referred to as RTSM (Reversed Two-Station Method), is in fact based on two simple observations. First, for a given seismic source, the source effects on the observed L_g ground motions are the same at the two stations, and they therefore can be cancelled out using a well-known spectral ratio technique. The spectral ratio technique does not remove the site effects and instrument errors associated with the two stations, however. It was then discovered that the combined station site effects and the unknown instrument errors at the two recording stations can be cancelled by "sending" the L_g signals back and forth — once in each direction — along a fixed waveguide containing the inter-station path segment, the signal emitters being the pair of seismic sources positioned as shown in Figure 12. The RTSM method has since been extensively tested in the Eastern Canadian proving ground using natural earthquakes and industrial mineblasts from Ontario, Quebec and New Brunswick as seismic sources. The results have shown that L_g amplitude reduction due to attenuation of as low as 10% or less can be reliably measured even though the individual station site amplifications alone are found to differ by a few tens to a few hundred percent. As demonstrated by Chun *et al.*[14], the reliability of the RTSM method for measuring L_g wave attenuation is unaffected at high frequencies (>5 Hz) where site effects are particularly strong.

Towards Understanding P_n Propagation and Attenuation

In the above, a novel technique for extracting subtle L_g attenuation effects in the presence of strong contaminating factors was discussed. Achieving similar results for the equally important companion regional phase P_n proved to be a difficult task because of the added uncertainty concerning the manner in which the P_n energy spreads out geometrically, a phenomenon unrelated to anelastic seismic attenuation. This uncertainty is rather unique to the P_n wave and, as far as we are aware, there have never been published methods for experimental determination of the geometrical spreading of the P_n wave. It has recently been pointed out[15] that the disagreements among the P_n practitioners regarding the P_n geometrical assumption have been the main cause of disparity among the published P_n attenuation for any given region. This is rather unfortunate in light of new research results implicating great importance of high-frequency P waves in detecting and identifying decoupled underground nuclear explosions[16].

Recently, Zhu *et al.*[17] and Chun *et al.*[18] extended the RTSM method and demonstrated that the extended version is capable of performing simultaneous determinations of the P_n geometrical spreading and the P_n attenuation. The demonstrations were carried out using a large body of P_n recordings from Eastern Canada Telemetered Network stations. The results show that stable path attenuation measurements can be made in the low attenuating Canadian Shield over distances as short as 100 to 200 km. Spatial resolution on this scale is a valuable asset in seismic monitoring of low threshold nuclear test ban treaties. A schematic drawing for the P_n waves can be seen in Figure 7.

Cloning: A Method of Seismic Network Calibration

While developing the RTSM attenuation measurement method, the University of Toronto team came upon a second discovery: a simple technique of turning all stations of a seismic monitoring network into nearly identical "clones," each capable of mimicking the characteristics of a pre-selected master station[19]. Technically, the procedure is called seismic network calibration. In essence, the core procedure in network calibration centres upon the determination of relative differences in the combined net effects arising from station geology and instrument characteristics. We have shown that such relative differences can in fact be measured very reliable for both the L_g wave[20] and the P_n wave[21] — using either RTSM or PSM (power spectral method), both developed by the University of Toronto team.

Once calibrated, the network stations will process the incoming seismic signal in the same manner, thus preserving any "earthquake-like" or "explosion-like" features that the arriving seismic signals happen to have, immediately before being subjected to near-station site effects and instrument errors. Also preserved is the relative signal strength — a crucial piece of information needed for the construction and subsequent use of the empirical magnitude/yield relation for estimating the size of underground nuclear explosions.

Network calibration largely eliminates the need for using multiple seismic records for each given event in order to "average out" unknown site effects and, to a lesser extent, instrument errors. By requiring fewer recording stations per seismic event, a calibrated seismic network has in effect a lower source identification threshold and is better equipped to handle adverse monitoring situations than is an uncalibrated counterpart. By virtue of their being individually calibrated to mimic the frequency response characteristics of a pre-selected master station, network stations can be relocated (to quieter or more strategic locations), refurbished, or added or deleted (one at a time) without incurring serious disruption to the ongoing monitoring activities.

The ability to accurately map out the P_n and L_g attenuation permits forensic seismologists to make appropriate propagation corrections for explosions occurring at sites, both declared and undeclared. The ability to turn into clones a group of monitoring stations helps ensure that an explosion too small to be well recorded by more than a few stations can nevertheless be subjected to reliable source identification and yield estimation analyses.

Chapter 8: Discussion and Conclusions

The availability of a large body of historical nuclear explosion data from Yellowknife Seismic Array has made possible accurate characterizations of P wave attenuation effects along the paths linking this quiescent Canadian listening post with seven of the most active nuclear test areas in the world. The results directly affect the YKA's future capability of making reliable teleseismic yield estimations. The University of Toronto team has also shown that use of the revised P wave attenuation results leads to more interpretable nuclear explosion source functions, including instances of successful unmasking of pP, an elusive depth phase of great importance in seismic source identification and explosion yield estimation.

Our detailed investigation of the epicentral locations of more than 7,000 earthquakes has produced a clear picture of region-specific location correction terms for the YKA. These correction terms, obtained using conventional frequency-wavenumber analysis of vertical-component data, will enable the array to improve the accuracy of its preliminary epicentral determinations for early detection of potentially anomalous seismic events.

State-of-the-art recording instruments of the recently refurbished YKA have ushered in an era of broadband, three-component signal processing. Sophisticated signal processing theories are currently being incorporated into the wavefield decomposition computer codes under development at the University of Toronto. The new array instruments, with their large recording dynamic range and high fidelity, have also prompted the development of a new synthetic seismogram (extended Ray-Kirchhoff) method[22] aimed at taking a fuller advantage of the newly available recording capabilities.

The University of Toronto team has made significant advances in the area of close-in monitoring of the compliance with a future LYTTBT or a CTBT, enabling reliable seismic monitoring of events both at declared test sites and off those sites. Newly developed methods for high-resolution mapping of regional wave attenuation and precise seismic network calibration have effectively reduced the number of recording stations required per event for reliable yield estimation and seismic source identification.

One important implication emerging from our network calibration work is that the gap between the seismic detection threshold (m_b 2.0-2.5) and identification threshold (m_b 3.5) in low-attenuation regions such as the U.S.S.R., currently lying between 1.0 and 1.5 m_b unit for small regional events[23], is closing. As discussed earlier, lowering the identification threshold by less than 0.5 m_b unit will appear to be sufficient to permit monitoring of well-coupled explosions with yields down to a subkiloton level and decoupled explosions, with yields down to a level below 5 kilotons.

The approaches followed by the University of Toronto forensic seismology research team are cost-effective, non-intrusive and impervious to adverse monitoring conditions. Testing of these methods with data from the Canadian Shield proving ground has yielded results that are of particular significance in future assessments of the monitoring requirements in much of the Eurasian continent.

NOTES

1. U.S. Congress, Office of Technology Assessment, *Seismic Verification of Nuclear Testing Treaties*, OTA-ISC-361, (Washington, D.C.: U.S. Government Printing Office, May 1988) — henceforth referred to simply as OTA, May 1988.

2. OTA, May 1988.

3. OTA, May 1988.

4. OTA, 1988.

5. OTA, May 1988.

6. Chun *et al*, 1991a; Zhu *et al.*, 1991c.

7. Figure 7 is modified from Zhu *et al.*, 1991c.

8. Taken from Zhu *et al.*, 1991c.

9. See for example, a Kazakhstan seismogram appearing in the February 24, 1987 issue of *Eos*, American Geophysical Union.

10. Chun *et al.*, 1991b.

11. Figure 10 is adapted from Chun *et al.*, 1991b.

12. Figure 11 is also adapted from Chun *et al.*, 1991b.

13. Figure 12 is adapted from Chun *et al.*, 1987.

14. Chun *et al.*, 1987.

15. For example, Chun *et al.*, 1989a.

16. OTA, May 1988.

17. Zhu *et al.*, 1991c.

18. Chun *et al.*, 1991a.

19. Chun *et al.*, 1989b.

20. Chun *et al.*, 1987; 1989b.

21. Chun *et al.*, 1989a; Chun *et al.*, 1991a; Zhu *et al.*, 1991c.

22. Zhu *et al.*, 1989.

23. OTA, May 1988.

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