THE POTENTIALITIES OF REGIONAL SEISMIC MONITORING

Vladimir V. Kovalenko and Marat S. Mamsurov

Research Institute of Pulse Technique

Sponsored by the Preparatory Commission for the
Comprehensive Nuclear-Test-Ban Treaty Organization

Contract No. 00/20/5020

ABSTRACT

Reliable recording of seismic events at regional distances is a necessary requirement for accurate location of these events, given that the typical spacing of the International Monitoring System (IMS) stations with respect to one another is 1,000 to 2,000 km, i.e., regional distance. Given an IMS system with a detection threshold in the range of 3.0 - 3.5 m_b, equivalent to approximately 0.5 kT of TNT, improving the 90% confidence level in location will be a powerful instrument for constraining potential violators of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). A simple method for assessing travel-time measurement and model errors in seismic location procedures is proposed for the phases Pn, Pg, Sn, and Lg. The estimates may be useful as the first approximation for work on the kinematic calibration of seismic stations.

KEY WORDS: seismic, regional, potentialities

OBJECTIVE

The objective of the work is to examine the potential of the seismic portion of the International Monitoring System (IMS) for accurate seismic event detection and location at the levels required by the CTBT. The estimates may be useful as the first approximation for work on the kinematic calibration of seismic stations.

RESEARCH ACCOMPLISHED

The CTBT is a nonthreshold treaty, but in accordance with paragraph 1, part III of the CTBT Protocol, each State Party shall, on a voluntary basis, provide the Technical Secretariat with notification of any chemical explosion with a yield of 300 T or greater of TNT equivalent detonated as a single explosion anywhere on its territory, or at any place under its jurisdiction or control.

Chemical explosions with yields less than 300 T of TNT equivalent, which are conducted in the interests of the mining industry or others, are so numerous and monitoring for them is so problematic, they are not considered good candidates for IMS calibration or CTBT monitoring. This threshold (>300 T of TNT equivalent) corresponds to the yield of an underground nuclear explosion of 0.5-0.6 kT (m_b=3.7-3.8). Expert opinion in the field of nuclear weapon development holds that the threshold of 1- to 2-kT yield is near the minimum test size useful for military purposes.

The configuration of the seismic stations of the IMS is such that the majority of them register seismic events at regional distances, where signal-to-noise ratio (SNR) is rather large. The connection between magnitude and yield of explosions at regional distances as shown in Archambeau et al (1991) can be approximated by the following formula:

$$m_b = A + B \log Y$$

where m_b = magnitude for body waves, Y = yield of explosion in kT, A and B = coefficients.

The value of $m_b \geq 3.0$ is chosen as a threshold of detection of seismic events by the International Data Centre (IDC) and the value of $m_b \geq 3.5$ is chosen as a threshold for the screening procedure. In this case the assessments for granite (A=3.92, B=0.81) and dry tuff/alluvium (A=3.32, B=0.81) give the following TNT equivalents (Table 1).

Table 1. TNT equivalents for threshold of 3-3.5 m_b

Magnitude	Granite, kT	Dry tuff/alluvium, kT
3.0	0.07	0.40
3.5	0.30	1.70

Thus, the system has high sensitivity for explosions in hard rock (e.g., granite) and sufficiently high for explosions in softer rock (e.g., tuff).

For a TNT equivalent of 0.5 kT, we get the following values for m_b (Table 2) for hard rock, which exceed the threshold of screening, and the following values for softer rock, which also exceeds the detection threshold.

Table 2. m_b values for explosions of 0.5-kT TNT equivalent

TNT equivalent, kT	Granite, m_b	Dry tuff/alluvium, m_b
0.5	3.68	3.08

The seismic portion of the IMS is planned to have a detection threshold of about m_b = 3 - 3.5 and a detection probability of at least 90% for the detection of underground nuclear explosions and other events with a TNT equivalent of at least 0.5 kT as a deterrent to potential violators of the CTBT.

Another important goal for the seismic portion of the IMS is a high degree of accuracy for seismic event location for the purpose of fielding an on-site inspection to confirm the nature of a suspicious event. In accordance with paragraph 3, part II (A) of the Protocol to the CTBT the area of an on-site inspection shall be continuous and its size shall not exceed 1,000 sq. km. There shall be no linear distance greater than 50 km in any direction. The seismic portion of the IMS must satisfy these requirements, but evaluations show that the IMS does not perform at this level for weak sources monitored at regional distances. The basic reason is insufficient accuracy of applied travel-time curves and IASPEI-91 tables, which are calculated chiefly for teleseismic distances. The problem may be resolved by construction of regional travel-time curves and 2-D and 3-D regional velocity models, which provide improvements in event location accuracy and allow us to satisfy the CTBT requirements. But there are certain restrictions, as discussed below.

The probability of locating the event epicenter with a confidence ellipsoid provided by a Gaussian distribution of possible errors could be described by following formula:

$$P_{hit} = 2\,[\,\Phi_o(k) - (1/\sqrt{2\pi})\,k \exp(-k^2/2)\,],$$ where

$$\Phi_o(k) = 1/\sqrt{2\pi} \int_o^k \exp(-t^2/2)\,dt;$$

$k = a/\sigma_x = b/\sigma_y = c/\sigma_z$ - parameter of distribution;

a, b, c are semi-axes of ellipsoid; and

σ_x, σ_y, σ_z are standard deviations along the axes of the basic coordinate system.

Except for nuclear explosions where $z \cong o$, we move to 2-D distribution, and when the errors are independent along x, y axes, the task can be reduced to two 1-D distributions. In this case:

$$P_{hit} = 1 - \exp(-k^2/2) \text{ where } k = a/\sigma_x = b/\sigma_y$$

In accordance with the requirements of the Protocol to the CTBT, the area of error ellipse must be

$$S = \pi\, a\, b \leq 1000 \text{ sq. km}$$

and the large axis of the ellipse must not exceed 50 km ($a \leq 25$ km). The probability of locating the event's epicenter within the error ellipse must be at least 90 % (Phit $\geq$ 0.9). In this paper, we use an ellipse with the utmost permissible characteristics: a=25 km, b=1000/πa=12.74 km. For Phit=0.9, k=2.146, σ_x=a/k=11.65 km, σ_y=b/k=5.94 km.

Another extreme case is the circular error with $R=\sqrt{1000/\pi} \cong 18$ km, $\sigma_r=18/2.146=8.39$ km. Given an event and using an appropriate basic velocity model of regional phases Pn, Pg, Sn and Lg, we have a root-mean-square (rms) value for the total errors (σ_t), corresponding to a location accuracy for elliptical and circular errors as given in (Table 3).

Table 3. The permissible significance of the total errors (σ_t, sec)

Regional phases	**Phase velocity, km/sec**	a = 25 km	R = 18 km
		σ_t for Phit=0.9/0.7	
Pn	8.00	1.46/2.01	1.05/1.45
Pg	6.00	1.94/2.68	1.40/1.93
Sn	4.62	2.52/3.48	1.82/2.51
Lg	3.50	3.33/4.60	2.40/3.31

The circular case is not very tolerant of errors. When we pass from elliptical to circular error distributions, coordinates along the large and small axes of the ellipse vary in sufficiently narrow limits: $18 \leq x \leq 25$ km and $12.74 \leq y \leq 18$ km. The latter indicates that the CTBT goal for accuracy of seismic event location is difficult to meet.

One may use other accuracy estimations for velocity models for regional phases. Figure 1 presents two 1-D velocity models of Pn for the east European platform: A (Mooney, 1999) and B (Dainty et al, 2000). For the calculations, we use the following values for average-weighted velocity (Vaw):

$$Vaw = \sum_i^n \Delta h_i v_i \,/\, \sum_i^n \Delta h_i \quad \text{where}$$

Δh_i = thickness of i-layer ;

v_i = average velocity in i-layer; and

n = number of layers.

For A, the thickness of the Moho is about 41 km, the path of Pn propagation in the upper mantle is 159 km, and the average velocity is 8.28 km/s; for B - the same characteristics are respectively 40, 160 km and 8.30 km/s. In spite of that, model A is more detailed. As a result average-weighed velocities are practically equal for 7.9 km/s and a corresponding value of σ_t = 1.475 sec.

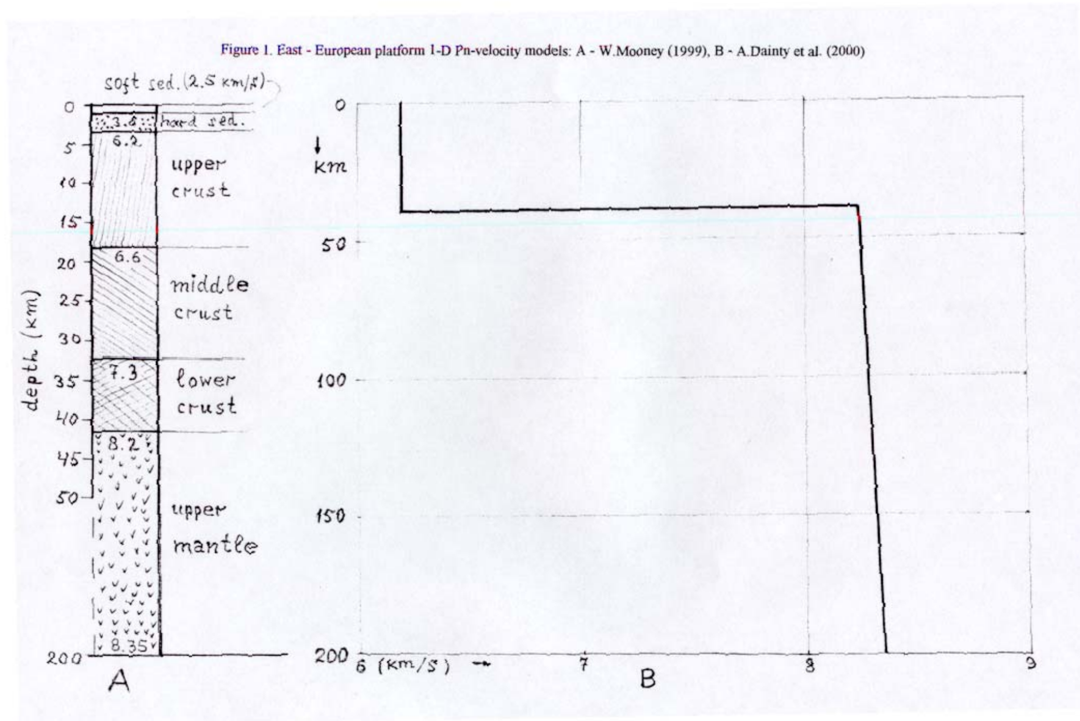

Figure 1. Two 1-D Velocity Models for the east European Platform

The permissible total error σ_t is usually presented in the form of two components: model σ_{mod} and measurement σ_{meas} errors. The first depends on the model chosen for seismic wave propagation and the character of statistical scattering of observed data by means of which the model travel-time curve is built The second is determined by the seismic wave arrival time measurement errors. For the squares of standard deviations, we can write:

$$\sigma_t^2 = \sigma_{mod}^2 + \sigma_{meas}^2 \ .$$

Decreasing of the modeling error is related to improvement of our knowledge of the structure of the earth's crust and upper mantle, and using more reliable velocity models. Decreasing the measurement error substantially depends upon signal-to-noise ratio (SNR). If SNR increases, σ_{meas} could decrease to the required level.

Bondar (2000) represents the dependencies of standard deviations of the measurement error for arrival time of the regional phases Pn, Pg, Sn, Lg versus SNR. At certain SNR values, the standard deviation is not to exceed 1 sec for Lg and 0.5 sec for Pn, Pg and Sn.

For regional phases Pn, Pg, Sn and Lg, Fig. 2 shows the modeling error dependency via distance for global model IASPEI - 91 (1) and two regional models: the Baltic shield (2) and the central part of the east European platform (3). For regional distances of up to 12 degrees, the errors for the Baltic shield model and Pn, Sn, Lg (North et al, 2000; Bondar et al, 1997) approximately correspond to the data in Table 3.

For Pg, the errors exceed the permissible level. This can possibly be explained by the insufficient accuracy of the earth crust model to real conditions (in this case, a 1-D model was used). As Figure 2 shows, when distance increases, the difficulties for providing the required modeling accuracy increase as well.

Figure 2. Pn, Pg, Sn, Lg modeling errors: IASPEI-91 (1), Baltic shield (2) and East - European platform (3)

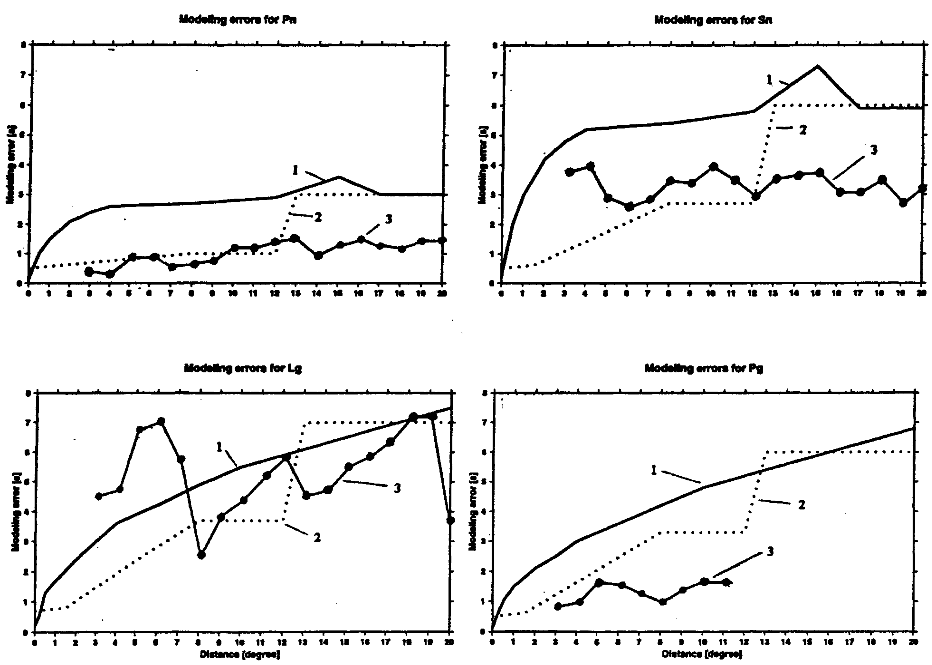

Figure 2. Pn, Pg, Sn, Lg Modeling Errors

Modeling errors from the regional model of the central part of the east European platform (Kirichenko et al, 2000) are essentially differentiated from analogous dependencies for the Baltic shield model, but Pn and Pg correspond considerably better to the Table 3 data. The Baltic shield is a structural uplift of the northwestern part of the east European platform, where its pre-Cambrian folded foundation comes out on the surface. The geological similarity between the provinces also confirms the data, which were generated with the help of 1-D velocity models for northern Eurasia (Dainty et al, 2000). Serious differences in changes in modeling errors for the above models apparently depend on the statistical insufficiency of the observed data and indicate the necessity for further development of the models.

CONCLUSIONS AND RECOMMENDATIONS

For the CTBT to be effective, the IMS requires a detection threshold for ~ 0.5 kT yield or an mb of 3.0 to 3.5 for nuclear and large chemical explosions with at least a 90% confidence level. To satisfy these requirements on accuracy of seismic event location, the mislocation of event epicenters must change from 18 km to 25 km for elliptical errors and from 8 km to 12 km for circular errors.

Selecting the regional seismic wave velocities, which are of interest for us, and comparing them with permissible deviations of the coordinates, we receive permissible standard errors for the required location accuracy. The effectiveness of assessments is enhanced if we use velocity models for the earth's crust and upper mantle and averaged values of seismic wave propagation velocity.

Results obtained should be considered only as a first approximation in the solution of a given problem. For more exact and full assessment of the task of determination of potential possibilities of the IMS, it is necessary to inventory all spectra of magnitude and space-time corrections for stations and arrays for the IMS.

In spite of the opinion of skeptics, the seismic portion of the IMS with well-calibrated stations and lower thresholds of recording of underground nuclear explosions can become a powerful instrument for deterring potential CTBT violations.

REFERENCES

Archambeau , C.B. et al (1991), Scientific and Technical Principles for Treaty Monitoring , *Verification,* Moscow, "MIR".

Mooney, W. D. (1999), Crustal and Upper Mantle Seismic Velocity Structure of the Former USSR, Proceedings of the 21st Seismic Research Symposium, Las Vegas, Nevada.

Bondar, Istvan (1998), Evaluation of PIDC Error Ellipses, Technical Report CMR-98/23, Arlington, VA, USA.

North, Robert, Xiaoping Yang, and Keith Mc Laughlin (2000), Source Specific Station Corrections for Regional Phases at Fennoscandia Stations - A Model for IMS Calibration Efforts, Location Calibration Workshop, Oslo, Norway.

Bondar, Istvan and Vladislav Ryaboy (1997), Regional Travel-Time Tables for the Baltic Shield Region, Technical Report CMR-97/24, Arlington, USA.

Kirichenko, V. V. and Yu. A. Kraev (2000), Development of Regional Travel -Time Tables for Different Geotectonic Provinces of Northern Eurasia, Proceedings of the 22nd Annual DOD/DOE Seismic Research Symposium, New Orleans, USA.

Dainty, A.M. et al (2000), 3-D Modeling Approach to Refine Location of Regional Seismic Events in Western Areas of Northern Eurasia and North America, RF/US Working Group, Third Status Report, CMR, Arlington, USA.