PERMISSIBLE SPATIO-TEMPORAL ERRORS OF SEISMIC EVENT LOCATION ACCURACY IN THE CONTEXT OF NUCLEAR-EXPLOSION-MONITORING REQUIREMENTS

Vladimir V. Kovalenko and Marat S. Mamsurov

Research Institute of Pulse Technique

Sponsored by the Comprehensive Nuclear-Test-Ban Treaty Organization

Contract No. 00/20/5020

ABSTRACT

Permissible ranges of distance-dependent modeling errors for the travel time of regional seismic waves and a new inter-epicenter criterion for estimation of the accuracy of seismic event location are considered. Together they provide a spatio-temporal range of values to meet the requirements of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) for seismic event location accuracy.

OBJECTIVE

The objective is consideration of permissible ranges of distance-dependent modeling errors for the travel time of regional seismic waves and a new inter-epicenter criterion for estimation of the accuracy of seismic event location. Together they provide a spatio-temporal range of values to meet the requirements of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) for seismic event location accuracy.

RESEARCH ACCOMPLISHED

The accuracy of seismic event location is ordinarily characterized by error ellipse sizes and the confidence level of the placement of the event epicenter into a given ellipse. In accordance with the Protocol to the CTBT (par. 3, p. II A) the error ellipse sizes must not exceed certain maximums. Studies by Mamsurov (2001) and Kovalenko and Mamsurov (2001, 2002) evaluated these restrictions and showed that for implementation of the CTBT requirements the root-mean-square (RMS) errors for travel time (σ_{tr}) of regional seismic phases must not exceed the values presented in Table 1 at a confidence level 0.9 for the error ellipse.

Table1. Permissible RMS deviations of travel times for regional seismic phases

Regional phases	Phase velocities, km/sec	Permissible RMS deviations of travel-times, $\sigma_{tr.per}$, sec
Pn	8.00	1.46
Pg	6.00	1.94
Sn	4.62	2.52
Lg	3.50	3.33

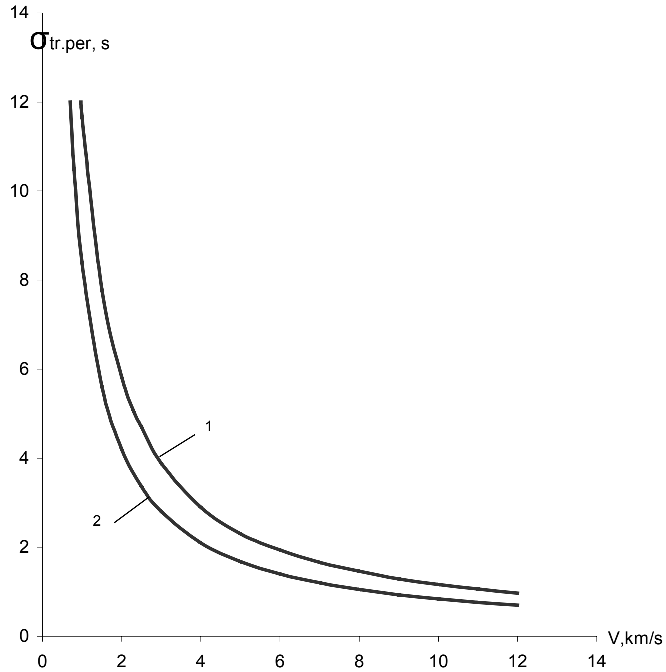
The estimates were made for typical phase velocities of seismic waves but can be made, as was shown in the cited works, for weighted averages of these velocities to match a given seismic wave velocity model. Thus, for any velocity of regional seismic wave (V, km/s) it is possible to find the maximum permissible travel-time error ($\sigma_{tr.per}$), which provides the required CTBT accuracy of seismic event location. This error for an uncertainty ellipse at 90 % confidence level depends on the wave velocity and the nature of the4 error ellipse. For example, $\sigma_{tr.per}$ = 11.65/V for an "elliptical" error ellipse and 8.39/V for a circular error ellipse (Figure 1), where σ_x=11.65 km (semi-major axis) and σ_r = 8.39 km, respectively (Kovalenko and Mamsurov, 2001, 2002). Figure 1 presents these relations as two isosceles hyperbolas, whose asymptotes are coordinate axes; by means of this Figure it is possible to estimate the value of maximum permissible travel time error for any regional phase.

Following Beall *et al*. (1997) σ_{tr} can be presented as:

$$\sigma_{tr}^2 = \sigma_{md}^2 + \sigma_{ms}^2 \qquad (1)$$

Where: σ_{md} – modeling error, characterizing the error of the velocity model or hodograph with respect to the actual properties of the medium of seismic wave propagation;

σ_{ms} –error of measuring of the seismic waves arrivals.



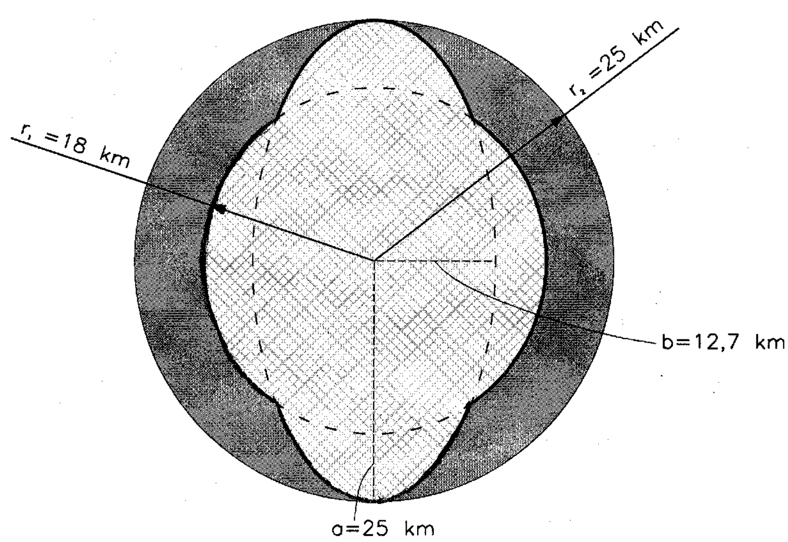


Figure 2. The field of permissible Inter-epicenter distances

Since σ_{ms} can be reduced by increasing signal/noise ratio (for example, to 0.5 sec and less for Pn waves), the dominating contribution to travel-time RMS error is the modeling error.

The simplest way of estimating modeling errors and their dependence on distance is from a typical hodograph:

$$T - R/V_{red} = (A \pm \sigma_A) - (B \pm \sigma_B) R \qquad (2)$$

Where: T – travel-time, R – distance, V_{red} – reduction velocity, A and B – regression constants, σ_A and σ_B – RMS errors for these constants.

As an example consider hodographs and their modeling errors for the East-European platform (Starovoit, *et al*. 2000). The regional hodograph parameters are given in Table 2, where r – correlation coefficient, RMS – travel-time deviation from averaged hodograph, N – number of observations. Data have been grouped so that the best approximation of the hodograph to observed data in the sense of minimum RMS deviation was provided. Modeling errors, calculated for these hodographs, and presented as RMS deviations of experimental data from the hodograph for sliding two degree windows with 50% overlap are shown in Table 3.

Table 2. Parameters of regional hodographs

Phases	Distance, km	Vred, km/s	A	σ_A	B	σ_B	N	R	RMS, sec
Pn	250-1150 1151-2500	8.00 8.00	7.867 13.806	0.351 0.402	0.0040 0.0094	0.0005 0.0002	51 218	0.78 0.94	0.8 1.3
Pg	250-1300	6.00	1.012	0.096	0.0075	0.0012	67	0.63	2.6
Sn	250-2500	4.62	15.640	1.420	0.0055	0.0008	138	0.52	4.1
Lg	250-2500	3.50	0.286	1.644	0.0063	0.0014	81	0.46	5.5

Table 3. Modeling errors for regional hodographs (sec).

Phases	Distance, degrees																	
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Pn	0.5	0.4	0.9	0.9	0.6	0.7	0.8	1.2	1.2	1.4	1.6	1.0	1.3	1.5	1.3	1.2	1.5	1.5
Pg	0.9	1.0	1.7	1.6	1.3	1.0	1.4	1.7	1.7									
Sn	3.8	3.9	2.9	2.6	2.9	3.4	3.3	3.9	3.4	2.9	3.5	3.8	3.7	3.0	3.0	3.5	2.7	3.2
Lg	4.5	4.7	6.7	7.0	5.7	2.6	3.8	4.4	5.1	5.7	4.5	4.7	5.5	5.8	6.3	7.1	7.1	3.7

Taking into account σ_{ms}= 0.5 sec for Pn and Pg waves and using modeling errors from Table 3 we see that for this case in all distance ranges $\sigma_{tr} < \sigma_{tr.per}$ in accordance with Table 1. However, modeling errors are too big for Sn and

Lg waves and the requirements on location accuracy are not satisfied, indicating the necessity of improvement of the model

Modeling errors play an important role in calculation of Station-Specific Source Corrections (SSSCs) for heterogeneous tectonic regions (Xiaoping *et al*., 1998, Firbas, 1999).

Besides modeling error, an additional criterion is needed for reliable estimation of seismic event location. At present a criterion is used based on covering the true coordinates of the event epicenter by the error ellipse (Bondar, 1998). This criterion is contradictory, because reduction of accuracy and increasing error ellipse size enables coverage of the event epicenter, while for a high-accuracy system with a small error ellipse, this in many cases becomes impossible, although this does not indicate low quality for such a system.

An error ellipse may not cover the true epicenter, or may have an area exceeding 1,000 sq. km, but CTBT requirements can still be executed, since in most practical cases we are interested in how closely the extent epicenter determined by the observing system approaches the true location or to a GT event epicenter, chosen as standard. A less contradictory and more sensitive criterion of seismic event location accuracy is the estimation of inter-epicenter distance:

$$\Delta = \sqrt{(\lambda_2 - \lambda_1)^2 + (\varphi_2 - \varphi_1)^2} \qquad (3)$$

where Δ - distance between the true epicenter with coordinates (φ_1, λ_1) and the epicenter determined by the observing system with coordinates (φ_2, λ_2). It is necessary to also take into account RMS deviations of coordinates $\sigma_{\lambda 1}, \sigma_{\lambda 2}, \sigma_{\varphi 1}, \sigma_{\varphi 2}$ if they are accessible.

In accordance with CTBT requirements the inter-epicenter distance must not exceed 50 km in any direction, while the epicenter must be inside or at the boundaries of an error ellipse, whose area is less than or equal to 1,000 sq. km with a given level of confidence.

Criterion (3) consists of two zones (Figure 2). The first zone is a circle, with radius $\mathbf{r}_1$= 18 km and area 1,000 sq. km; in any direction the inter-epicenter distance does not exceed 36 km:

$$\Delta \leq 36 \text{ km} \qquad (4)$$

The boundary of the second zone is a circle of $\mathbf{r}_2$ = 25 km radius; in any direction the inter-epicenter distance does not exceed 50 km:

$$\Delta \leq 50 \text{ km} \qquad (5)$$

However, the area of the second circle (1963 sq. km) is almost twice as large as the CTBT value. Therefore, for implementation of the CTBT requirements, both epicenters, true and determined, must be inside or at the boundaries of an ellipse, whose area is 1,000 sq. km and semi-axes are: a= 25 km and b = 12.7 km, inscribed in the second circle. The conditions of getting of both epicenters inside and at the boundary of such ellipse leads to two inequalities:

$$\begin{aligned} (\lambda_1/25)^2 + (\varphi_1/12.7)^2 &\leq 1 \\ (\lambda_2/25)^2 + (\varphi_2/12.7) &\leq 1 \end{aligned} \qquad (6)$$

Thus the application of the proposed criterion consists of calculation of Δ, checking inequality (4) and, if $\Delta > 36$ km, testing of inequalities (5) and (6).

If $\Delta > 50$ km we overrun the permissible zone and it is necessary to take measures on reduce the modeling errors and increase the trustworthiness of the model.

Results of application of the proposed criterion are presented in Table 4, which confirms the effectiveness of estimating the seismic event location accuracy by the inter-epicenter distance Δ. The CTBT requirements for seismic event location accuracy are satisfied for all events of the Table 4, even though the simplest form of criterion (Δ≤ 36 km) is used. In no case was a transition necessary to the second zone of the criterion (inequalities 5 and 6). We note that IASPEI-91 tables were used in this case in spite of the resulting problems: for all events the area of the error ellipse noticeably exceeded the permissible value, and for the event on 21.05.97 the error ellipse did not cover the true epicenter). Use of SSSCs (3-D) (Ryaboy *et al*. 2001) improved the accuracy of epicenter coordinate estimation, but for three events the area of the error ellipse still exceeded the permissible norm. Thus, as Table 4 shows, using only IASPEI-91 tables and the criterion of inter-epicenter distance it is possible to solve the problem without resorting to even 1-D regional models.

Of course, in a case when Δ>50 km, it is necessary for satisfaction of the CTBT requirements on location accuracy to use the newest geological and geophysical methods for construction of 1-D regional hodographs and models and for transition to 2-D and 3-D regional models if more simple methods do not give the required result. But at every stage it is reasonable to make sure that the possibility of simpler approaches was really exhausted.

Table 4. The estimation of seismic event location accuracy with the use of the criterion of the inter-epicenter distance

Event	**IASPEI-91**			**Criterion of the Inter-epicenter distances**			**SSSCs (3-D)**		
	Error of epic.loc., km	Square of err. ell., sq.km	Err.ell. covers of epic.	Distance between epic., km	Square of circle/ell., sq.km	Err.ell. covers of epic.	Error of epic.loc., km	Square of err. ell., sq.km	Err.ell. covers of epic.
333140, 17.04.95	22.4	2,399	+	23.0	415	+	7.2	478	+
Chem.Exp., 03.04.66	20.7	3,386	+	20.0	314	+	9.0	471	+
PNE, 10.12.61	28.3	3,281	+	27.0	572	+	4.5	479	+
PNE, 24.09.83	28.6	3,902	+	27.3	585	+	8.8	2,780	+
313623, 11.03.95	8.9	3,855	+	8.0	50.2	+	7.4	2,634	+
20307517, 27.01.99	11.5	3,012	+	10.7	89.2	+	2.2	773	+
1004498, 12.04.97	13.8	1,430	+	10.0	78.5	+	2.6	300	+
1108893, 16.08.97	17.8	2,278	+	11.3	101	+	6.2	528	+
271133, 5.01.95	28.3	4,113	+	29.0	660	+	7.0	873	+
1043706, 21.05.97	17.3	3,171	-	17.0	227	+	5.3	640	+
Ev73Sep19	18.9	4,830	+	19.0	283	+	6.7	1,078	+
Ev85Jul 18	24.2	5,507	+	24.0	452	+	9.9	843	+

CONCLUSIONS AND RECOMMENDATIONS

A simple method is provided of assessment of maximum permissible travel-time errors for regional seismic phases that provide implementation of the CTBT requirements on accuracy of seismic event location.

For regional hodographs a simple method is recommended of estimating modeling errors, the dominant constituent of total travel-time errors.

The limitations of the presently used criterion of seismic event location accuracy by error ellipse size and coverage of the true epicenter coordinates for a given event are noted.

A less contradictory and more effective criterion of estimation of seismic event location accuracy is offered based on assessment of the distance between the epicenter determined by the observing system and the true, given or GT location for the same event.

REFERENCES

Beall, G. *et al*. (1997), New style measurement and model errors, Center for Monitoring Research, CCB Memo CMR-97, Arlington, Virginia.

Bondar, I. (1998), Evaluation of PIDC Error Ellipses, Technical Report CMR-98/23, Arlington, Virginia.

Firbas, P. (1999), Calibration Based on Ground Truth Data and 3-D Modeling: Framework and Feasibility Study for Western Europe, Workshop on IMS Location Calibration, Oslo, Norway.

Kovalenko, V. and M. Mamsurov (2001), The Potentialities of Regional Seismic Monitoring, Proceedings of the 23rd annual DTRA/NNSA Seismic Research Review, Jackson Hole, Wyoming.

Kovalenko, V. and M. Mamsurov (2002), About Estimation of the Seismic Event Location Accuracy, Fourth Workshop on IMS Location Calibration, Oslo, Norway.

Mamsurov, M. (2001), Threshold Possibilities of the International Seismic Monitoring System, Third Workshop on IMS Location Calibration, Oslo, Norway.

Starovoit, O. *et al*. (2000), Regional Travel Time Curves at East-European Platform for Improved Location of the Seismic Events, Second Workshop on IMS Location Calibration, Oslo, Norway.

Xiaoping, Y. *et al*. (1998), SSSCs for Regional Phases at IMS Stations in North America and Fennoscandia, Technical Report CMR-98/46, Arlington, Virginia.

Ryaboy, V. *et al*. (2001), SSSCs Based on 3-D Modeling for Pn, Sn, and Pg Phases at IMS Stations in Northern America, Third Workshop on IMS Location Calibration, Oslo, Norway.