A PLAN FOR LOCATION CALIBRATION OF IMS STATIONS IN AND NEAR KAZAKHSTAN

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ABSTRACT

For purposes of monitoring compliance with the Comprehensive Nuclear Test-Ban Treaty, it is desirable to be able to locate seismic events routinely to within an uncertainty not greater than 1000 square km. From more than five years of experience with publication of the Reviewed Event Bulletin (REB) by the Prototype International Data Centre (PIDC), resulting in estimated locations for more than 100,000 seismic events, it is apparent that improved location accuracy is needed in order to reduce uncertainties below 1000 square km. In this paper, we outline a three-year program of applied research which commenced in March 2000 and which has the goal of achieving improved REB locations based upon data to be contributed to the International Data Centre from 30 IMS stations in Eastern Asia. Our first efforts will focus on the four IMS seismographic stations in Kazakhstan (AKT, BRV, KUR, MAK), together with IMS stations ZAL in Russia and AAK in Kyrgyzstan.

Following the recommendations of two “IMS Location Calibration Workshops” held in Oslo, Norway, in 1999 and 2000, our approach is to generate station-specific travel times for each observable seismic phase, as a function of distance and azimuth (and depth, where possible). Such travel times are obtained on the basis of (i) early studies based mainly on earthquake data (e.g. Nersesov and Rautian, 1964), (ii) Deep Seismic Sounding, and (iii) recent studies of nuclear and chemical explosions. We are also using (iv) an empirical approach in which phases are picked at IMS stations, for so-called Ground Truth events whose location is known quite accurately on the basis of additional data, obtained for example from local and regional networks.

INTRODUCTION

Major users of seismic data include: (1) those engaged in earthquake engineering and earthquake hazard mitigation; (2) researchers who improve our scientific knowledge of Earth's internal structure and the physics of earthquake processes; and (3) the national and international groups now being organized to monitor compliance with the Comprehensive Nuclear Test-Ban Treaty (CTBT). Although the most basic data in seismology for all these users are seismograms, in practice the great majority of those in (1) -- (3) who work with seismic data do not use seismograms directly. Instead they mostly use data products derived from seismograms. The most important of these products, are bulletins of seismicity.

In the last 20 years there have been enormous improvements in the quality and quantity of seismograms, associated with the development of feedback sensors and techniques of digital recording to permit high dynamic range across wide bands of frequency. And there is ongoing revolutionary improvement in access to seismogram data, as satellite communications and the Internet spread even to remote locations. It has therefore been frustrating to find that the quality of the principal data product derived from seismograms, the global bulletin of seismicity, has not yet seen the types of radical improvement needed by any of the user communities (1) -- (3). The US Geological Survey (USGS) and the International Seismological Centre (ISC) publish their bulletins months to years in arrears, using volunteered data of variable quality and methods of analysis that essentially have not changed for sixty years.

The Reviewed Event Bulletin (REB) of the CTBT monitoring community, produced by the Prototype International Data Centre (PIDC) from January 1995 to February 2000 and subsequently by the IDC in Vienna, is vastly improved over the other global bulletins in its timeliness of publication. However, both the REB location estimates, and the estimates of their uncertainty (error ellipses), are inadequate in terms of the requirements of the treaty that the REB is designed to support.

To appreciate what might be adequate, we can quote the CTBT Protocol, Part II, paragraph 3:

> “The area of an on-site inspection shall be continuous and its size shall not exceed 1000 square kilometers. There shall be no linear dimension greater than 50 kilometers in any direction.”

Also, paragraph 41(b) states (with reference to an On-Site Inspection request) that the proposed boundaries of the area to be inspected are to be specified on a map in accordance with paragraph 3. (Note that a circle of radius 18 km, has an area of about 1000 square km.)

These conditions amount to an extraordinary technical challenge for those at the IDC, who may have to estimate the location of an event that could become the basis of an on-site inspection request. The challenge will be especially difficult if the event is small and the IDC location estimate is based upon regional waves recorded at primary and auxiliary stations alone.

Note also that accurate location estimates are needed not only for events destined to be considered for on-site inspection. They are needed for essentially all of the events for which a set of detections can be associated, since in practice an interpretation of the location (including the event depth) is commonly used for screening at the IDC, and perhaps for rapid identification by National Data Centres. It can be important to know if an event is beneath the ocean, or possibly on land; if it is more than 10 km deep, or possibly near the surface; if it is in one country, or another.

One of the first statements of failure to meet these technical challenges was given by Robert North, reporting on GSETT-3 after about two years of REB production:

> “many of the events listed in the… (REB) are poorly located. The 90% confidence ellipses exceed 1000 sq. km for 70%, and 10000 sq. km for 30%, of all REB events. Furthermore, comparison by various countries of the locations produced by their own denser national networks with those in the REBs show that the REB 90% confidence ellipses contain the national network location less than half of the time … One feature… that is particularly troublesome is that many events will be recorded only at teleseismic distances, and that few will be recorded only to regional (< 2000 km) distances. Thus an appropriate means of implementing path-dependent teleseismic travel times, and of transitioning from these to regional travel time curves, will need to be developed.”

At the first Oslo Workshop on IMS Location Calibration, in January 1999, several speakers reported essentially the same problems, after four years of REB publication: purported 90% error ellipses were often much larger than 1000 sq. km, they did not include true locations 90% of the time, and depth uncertainties did not adequately represent errors in depth. For the REB of February 20, 2000 (the final REB produced before routine daily bulletin production was moved to the Vienna IDC), there were 15 seismic events with magnitude greater than or equal to 4. Of these 15 events, only 3 were located with confidence ellipses smaller than 1000 square km.

It is important to understand clearly why REB location estimates at present are so poor, since the error in measuring the arrival time of seismic waves is usually less than one second (and is usually less than 0.1 second when signal-to-noise ratios are good), and the velocity of seismic waves is less than 10 km/s in the Earth's outer layers where the events of interest occur and where the measurements are made. It would therefore appear that seismic sources can routinely be located to within a few km, and an areal uncertainty much less than 100 sq. km. In principle this conclusion is valid, nevertheless it does not apply at present, because we do not yet have a sufficiently good model of the Earth's velocity structure. It is the model errors, not the pick errors, which at present dominate the resulting location errors, at least for events of magnitude greater than about 4.5. The overall goal of improving locations based on seismic arrival times can be achieved only by reducing the effect of model errors.

At depths greater than about 200 km, the Earth's velocity structure is known quite accurately (i.e. to better than 1% at most depths, the biggest exceptions being in regions of subducting tectonic plates). The main difficulty is at shallower depths, i.e. within the crust and uppermost mantle, where the actual velocity of seismic waves may differ in unknown ways, perhaps by as much as 10%, from the velocity that we often assume (such as the velocity given by IASPEI91 or some other standard Earth model). The actual Earth also has non-horizontal interfaces, which are not allowed for in simple Earth models, and which can affect the azimuth of the arriving signal. As a consequence, the measured arrival times and directions of teleseismic waves are influenced in unpredictable ways by unknown Earth structure. The arrival times and directions of regional waves, which depend much more strongly on shallow structure, can be even more variable than teleseismic waves. For example if a seismic event is actually 1000 km from an IMS station and generates a regional wave that is detected at the station, and if the arrival is misinterpreted with a velocity that is wrong by 5%, then the event will be estimated from that observation alone as having originated at a distance that is incorrect by about 50 km.

When estimating event locations and their uncertainty, there are essentially only three ways to get around the practical problem of ignorance of Earth structure (i.e., model error):

(a) by using numerous stations at different azimuths around the source and thus averaging out the effects of the difference between the Earth's actual velocity structure and that of the model (which is usually assumed to be a structure in which velocity depends on depth alone);

(b) by building up information about the Earth's velocity structure and thus finding a more sophisticated and significantly more accurate three-dimensional model with which to interpret arrival times; and

(c) by “calibrating” the station (or array), so that in effect the source of interest is located with reference to another event, whose location is known accurately, and which preferably is not far from the source of interest. In this latter approach, the data for the unknown event is the difference in arrival times for the two events, as recorded at each station. From such data, we can often estimate accurately the difference in location between the known and unknown locations, and hence estimate the unknown location. Equivalently for enough calibration events, and using appropriate methods of smoothing, one can use empirically determined travel times for each seismic wave from each potential location to each station.

The US Geological Survey and the International Seismological Centre (ISC) rely upon (a) for routine processing, for then the effect of using an incorrect Earth model is reduced. The research community uses one or more of (a), (b), (c) but only in studying special sets of events, restricted to very limited regions. The IDC is restricted in the use of (a) since the REB is based on IMS stations alone. The IDC is therefore beginning to use methods (b) and (c). But even with great efforts based on hundreds of special studies, we will not know the Earth's three-dimensional shallow structure adequately on a global scale for decades, ruling out reliance on (b) alone in the short term, though this method can be used successfully for some regions. This leaves (c) as the most important short term method, and the authors of this paper completely concur with the February 1, 1999, report of the Oslo Workshop on IMS Location Calibration (see CTBT/WGB/TL-2/18) which stated that

> “such calibration is necessary in order to significantly improve the location precision of internationally reporting earthquake agencies,”

and that

> “no attempt has so far been made to include such corrections in routine location processing on a global scale.”

In March 2000, we began a three-year collaborative academic-industry research project led by Lamont and involving a consortium of five institutions. We have started an integrated series of projects, all with the goal of improving the capability to locate seismic events based on data acquired by International Monitoring System (IMS) stations in Eastern Asia. The 30 stations we are studying are listed in Table 1 and shown on a map in Figure 1. (This Figure also shows the location of non-IMS stations, that may provide data pertinent to our project. A station that is near an IMS station, and which can supply phase picks and/or waveforms that allow empirical travel times to be obtained, is called a surrogate station.) Our basic approach is to use numerous so-called "ground truth" seismic events in Eastern Asia that have been located accurately by regional or local networks, in order to obtain the travel times of key seismic phases from any point in the region, to any of the 30 IMS stations that are the focus of the project. These travel-times will in general be a function of distance and azimuth --- and depth. They must be determined as a continuous function of position, from the empirical discrete ground truth data; and they must be demonstrated to improve location estimates of new events, over the estimates obtained on the basis of current procedures (typically, based on the Earth model IASP91).

In the first project, the Lamont-Doherty Earth Observatory of Columbia University will work to obtain ground truth locations in Eastern Asia, whose errors are thought to be of the order of five km or better (so-called GT5 events); and that are expected to be large enough for detection at IMS stations, and in most cases recently enough for inclusion in the Reviewed Event Bulletin of the PIDC since 1995.

In the second project, the University of Wyoming will contribute observed travel times for about 3000 three-component recordings at stations widely deployed in the Soviet era to detect regional waves from 19 nuclear explosions carried out during the Deep Seismic Sounding program. This dataset is an invaluable resource for thorough calibration of major aseismic regions in Russia and Central Asia. We expect to be able to find analog seismograms for several of these 19 nuclear explosions, as recorded at Eastern Asia stations now identified as part of the IMS, or at stations that were operated at sites close to the IMS station locations (so-called surrogate stations).

In the third project, Mission Research Corporation will derive and test travel time surfaces, for IMS stations, that fit the ground truth data and Calibration Event Bulletin data. Specifically, MRC will work to obtain Source Specific Station Corrections (SSSCs) for each of the 30 IMS stations. An SSSC is the difference between what we believe to be our best model of the travel time (from any particular source location to a specific IMS station), minus the travel time for that path as given by the standard Earth model IASP91. URS Greiner Woodward Clyde will contribute ground truth data for India, Nepal, Pakistan, Tibet, and modeling experience with one- and two-dimensional structures; the University of Connecticut will contribute three-dimensional modeling experience. Both these organizations, and the University of Wyoming and Lamont, will work together in Project 4 to provide expected travel times to 30 IMS station locations in Eastern Asia. In this fourth project, we anticipate that a key role will be played by the approximately 70 Soviet-era Peaceful Nuclear Explosions that were widely recorded in Eurasia. Also, in the work of obtaining accurate locations (GT5 or better) of earthquakes, we shall use modern methods of estimating the locations of large numbers of earthquakes all together (see the article by Richards in the IRIS Newsletter of Fall 2000).

In the fifth project, members of the consortium will work together to evaluate the degree of improvement in location estimation, achieved by use of our SSSCs as compared to use only of the default Earth model (*iasp91*). This is the important step of validation, which must be demonstrated before SSSCs are deemed acceptable for operational use.

In the section which follows, we describe some of the particular datasets that are important to our project, for the IMS stations in and near Kazakhstan.

PS12	China	Hailar	49.27	119.74
PS13	China	Lanzhou	36.09	103.84
PS23	Kazakstan	Makanchi	46.80	82.00
PS25	Mongolia	Javhlant	47.99	106.77
PS29	Pakistan	Pari	33.65	73.25
PS31	Republic of Korea	Wonju	37.50	127.90
PS33	Russian Federation	Zalesovo	53.94	84.81
PS34	Russian Federation	Norilsk	69.40	88.10
PS35	Russian Federation	Peleduy	59.63	112.70
PS37	Russian Federation	Ussuriysk	44.28	132.08
PS41	Thailand	Chiang Mai	18.80	99.00
AS7	Bangladesh	Chittagong	22.40	91.80
AS20	China	Baijiatuan	40.02	116.17
AS21	China	Kunming	25.15	102.75
AS22	China	Sheshan	31.10	121.19
AS23	China	Xi'an	34.04	108.92
AS57	Kazakstan	Borovoye	53.06	70.28
AS58	Kazakstan	Kurchatov	50.72	78.62
AS59	Kazakstan	Aktyubinsk	50.40	58.00
AS60	Kyrgyzstan	Ala-Archa	42.64	74.49
AS68	Nepal	Everest	27.96	86.82
AS86	Russian Federation	Seymchan	62.93	152.37
AS87	Russian Federation	Talaya	51.68	103.64
AS88	Russian Federation	Yakutsk	62.01	129.43
AS89	Russian Federation	Urgal	51.10	132.36
AS90	Russian Federation	Bilibino	68.04	166.37
AS91	Russian Federation	Tiksi	71.66	128.87
AS92	Russian Federation	Yuzhno-Sakhalinsk	46.95	142.75
AS93	Russian Federation	Magadan	59.58	150.78
AS100	Sri Lanka	Colombo	6.90	79.90

Table 1. The list of 30 IMS stations, with coordinates as given in the original (1996) CTBT Protocol Annex, for which our project is to obtain Source Specific Station Corrections (SSSCs).

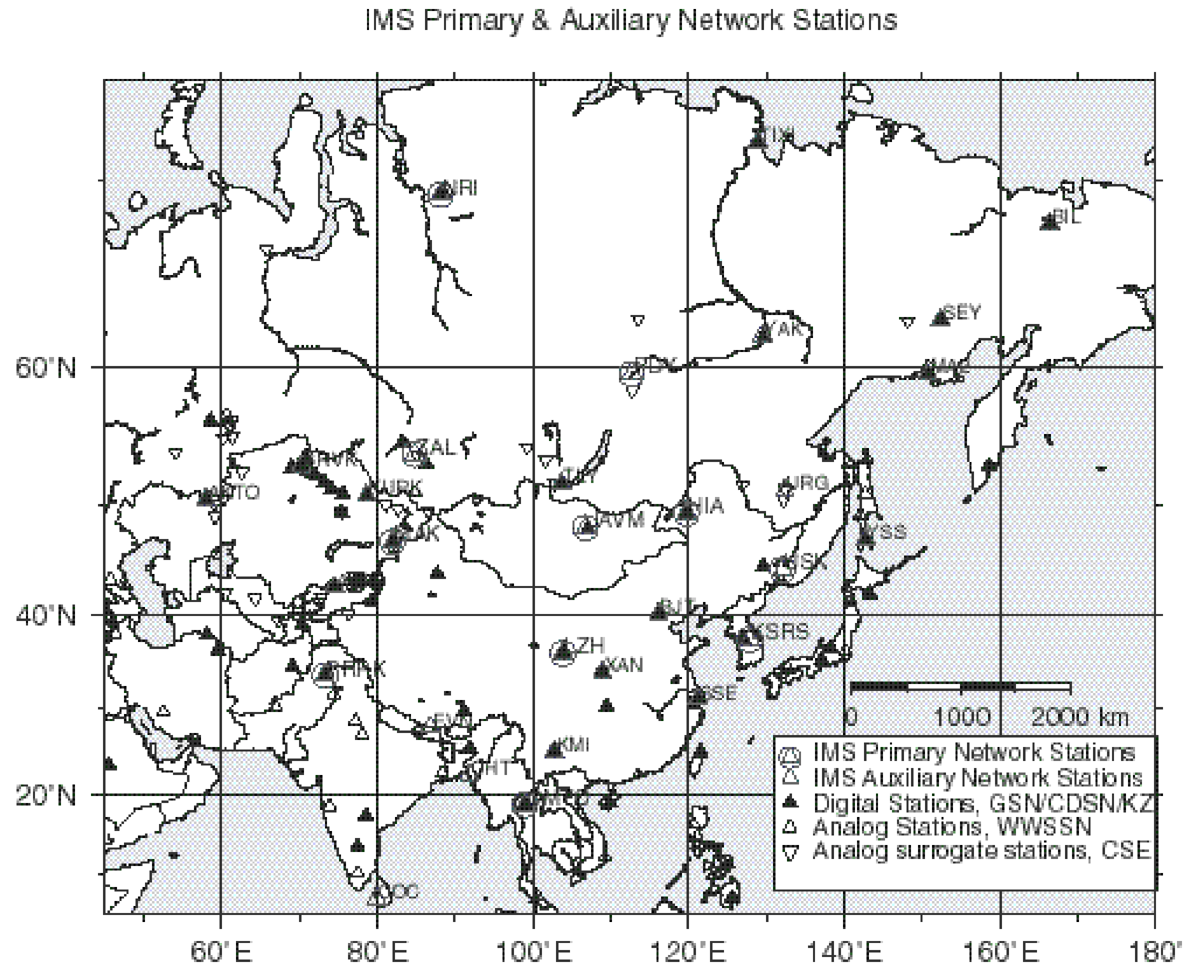

Figure 1. Map showing the location of 30 IMS primary and auxiliary stations in our project. Also shown, are some of the surrogate stations that may enable us to acquire empirical travel time data, relevant to calibrating IMS stations.

DATASETS RELEVANT TO CALIBRATION OF IMS STATIONS IN AND NEAR KAZAKHSTAN

From the very extensive literature on seismic travel times and crust/upper mantle structure in and near Kazakhstan, we note first the classic study of Nersesov and Rautian (1964), describing the early work on a “big profile” carried out by the Complex Seismological Expedition. Khalturin et al. (2001) used observations of small-magnitude underground nuclear explosions at the Semipalatinsk Test Site, and earthquakes with good locations, to obtain a version of the Nersesov and Rautian travel times which is adapted to this test site and surrounding areas. They located several small magnitude events on the test site with accuracy about 5 km using only a few stations. Their results were confirmed by comparison with ground truth information, obtained after the seismically-based locations had been estimated.

In addition, Table 2 lists 27 Deep Seismic Sounding (DSS) profiles in Central Asia. This Table is assembled from information in Antonenko (1984), Shatsilov (1993), Zunnunov (1985) and the book “Seismic Models of the Lithosphere of the main Geostructures in territory of the USSR” (1980).

MAJOR DSS PROFILES ON OR NEAR KAZAKHSTAN TERRITORY

N	Name or position	Profile end points	Length, km
1.	Turkestanski	42.5N 65.0E to 44.7N 75.0E	
	then to		
		46.3N 81.0E to 49.0N 83.4E	1,550
2.	Charsky - Sinyuha	49.3N 80.8E to 50.4N 83.2E	220
3.	Sayakski, first line	43.1N 74.9E to 46.5N 76.8E	
	second line	46.6N 77.3E to 51.1N 82.1E	600
4.	Aktogaysky	44.7N 78.6E to 47.5N 80.5E	350
5.	Kentierlausskiy	47.1N 72.9E to 47.5N 80.5E	570
6.	Zhalanash - Taldi-Kurgan	43.0N 78.5E to 45.0N 78.5E	220
7.	Issikski	43.3N 77.7E to 46.2N 77.3E	315
8.	Central Kazakhstansky	47.4N 70.7E to 49.0N 77.7E	540
9.	Issik-Kul - Balkhash	43.3N 77.0E to 46.0N 75.0E	430
10.	Slavgorodsky	46.2N 73.8E to 51.4N 77.5E	520
11.	Shchuchinsk - Severnoe	53.4N 71.6E to 56.3N 76.3E	700
12.	Karkaralinsky	48.8N 75.2E to 50.6N 69.2E	780
13a.	Temirtay-Petropavlovsk	50.3N 72.9E to 54.8N 69.4E	600
13b.	Balkhash-Temirtau	46.9N 75.0E to 50.3N 72.9E	500
13b.	Temirtay-Petropavlovsk	50.3N 72.9E to 54.8N 69.4E	600
14.	Uvanassky	43.6N 74.0E to 46.1N 65.2E	740
15.	Aris'- Balkhash	42.5N 68.7E to 45.7N 73.4E	510
16.	Temirtau - Kuybishev	50.3N 72.9E to 52.2N 54.0E	1,360
17.	Peschaniy	43.9N 68.8E to 47.0N 72.6E	460
18.	Karatau - Tengiz Lake	43.2N 70.5E to 50.2N 69.0E	900
19.	Kzil-Orda - Dzheti-Konur	44.8N 65.6E to 47.7N 68.8E	400
20.	Meridian	42.8N 67.4E to 49.5N 68.3E	740
21.	1-T-70	47.4N 65.8E to 48.6N 58.6E	550
22.	Aktyubinsky	50.0N 62.1E to 50.2N 57.5E	300
23.	Kopet-Dag - Aral Sea	40.0N 58.0E to 43.8N 61.3E	650
24.	Kandagachsky	49.0N 59.5E to 50.8N 52.0E	540
25.	Chelkar - Volgograd	48.5N 58.0E to 49.0N 54.OE	930
26.	OP-1 and 11	41.2N 54.5E to 52.3N 53.7E	1,680
27.	Farab - Tamdi-Bulak	40.0N 63.5E to 43.0N 65.0E	430

Table 2. List of Deep Seismic Sounding Profiles, using chemical explosions, conducted in or near Kazakhstan. Locations of these profiles are shown in Figure 2.

Figure 2 shows the location of these 27 profiles, some of which consisted of more than one segment. Table 3 gives the empirical travel time of Pn arrivals picked from seven DSS profiles in and near Kazakhstan, and Table 4 gives a simple (straight line) travel time as a function of distance, for the Pn wave on these seven profiles, and also the distance over which this time -- distance relation applies. Figure 3 shows seven values for the average Pn velocity obtained from the data associated with Tables 2 and 3.

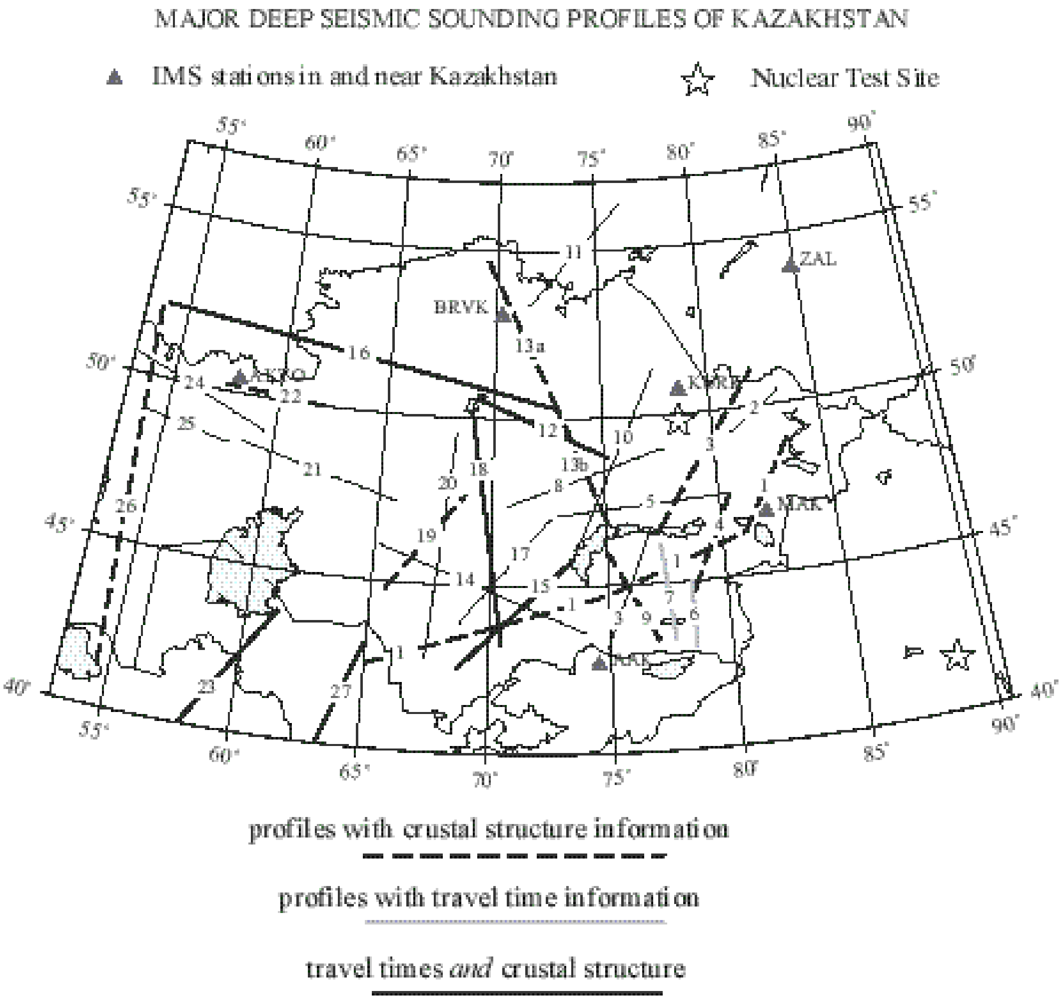

Figure 2. Map showing 27 DSS profiles in and near Kazakhstan. Profile numbers are consistent between Figures 2 and 3, and Tables 2, 3, 4.

Travel Time of Pn Arrivals for Seven DSS Profiles in & near Kazakhstan

	Profiles numbers on the map (Figure 2)							
R,km	6	7	15	16	18	23	27	IASPEI91
160	-	-	-	27.5	-	27.5	28.1	-
200	35.8	-	34.4	32.6	33.0	33.0	33.4	32.3
240	40.9	40.9	38.4	37.7	38.3	38.2	38.0	37.2
280	45.5	45.6	43.3	43.2	43.1	43.0	42.9	42.2
320	50.4	50.6	47.9	47.8	47.8	47.7	-	47.1
360	55.1	55.4	52.9	52.6	52.6	52.8	-	52.1
400	60.7	60.9	58.2	57.5	57.5	57.2	-	57.0
440	-	-	64.0	-	62.5	62.3	-	62.0
480	-	-	69.5	-	66.8	67.3	-	66.9
520	-	-	74.2	-	71.4	72.7	-	71.9
560	-	-	-	-	76.2	77.6	-	76.8
600	-	-	-	-	81.1	82.5	-	81.7
640	-	-	-	-	86.0	-	-	86.7
680	-	-	-	-	91.1	-	-	91.6
720	-	-	-	-	96.2	-	-	96.6
760	-	-	-	-	101.4	-	-	101.5
800	-	-	-	-	105.5	-	-	106.5
840	-	-	-	-	110.4	-	-	111.4
880	-	-	-	-	115.3	-	-	116.4

Table 3. Empirical travel times reported for seven DSS profiles (chemical explosions) in and near Kazakhstan. (Information from Zunnunov, 1985.) The numbering of profiles here is the same as in Figures 2 and 3. Thus, #6 - Zhalanash - Taldy-Kurgan. From N. Tienshan to North.
#7 - Issik. From N. Tien-Shan to Balkhash Lake.
#15 - From Aris' (42.4N; 69.0E) to NE to Balkhash Lake, across South Kazakhstan.
#16 - From Temirtau (50N; 73E) to WNW direction to South Ural.
#18 - From Karatay (43.2N; 70.5E), S. Kazakhstan, across the Central Kazakhstan to Tengiz Lake.
#23 - From West Turkmenia to eastern part of Aral Lake.
#27 - Farab - Tamdibulak. West Uzbekistan, between Amu-Darya and Syr-Darya rivers.

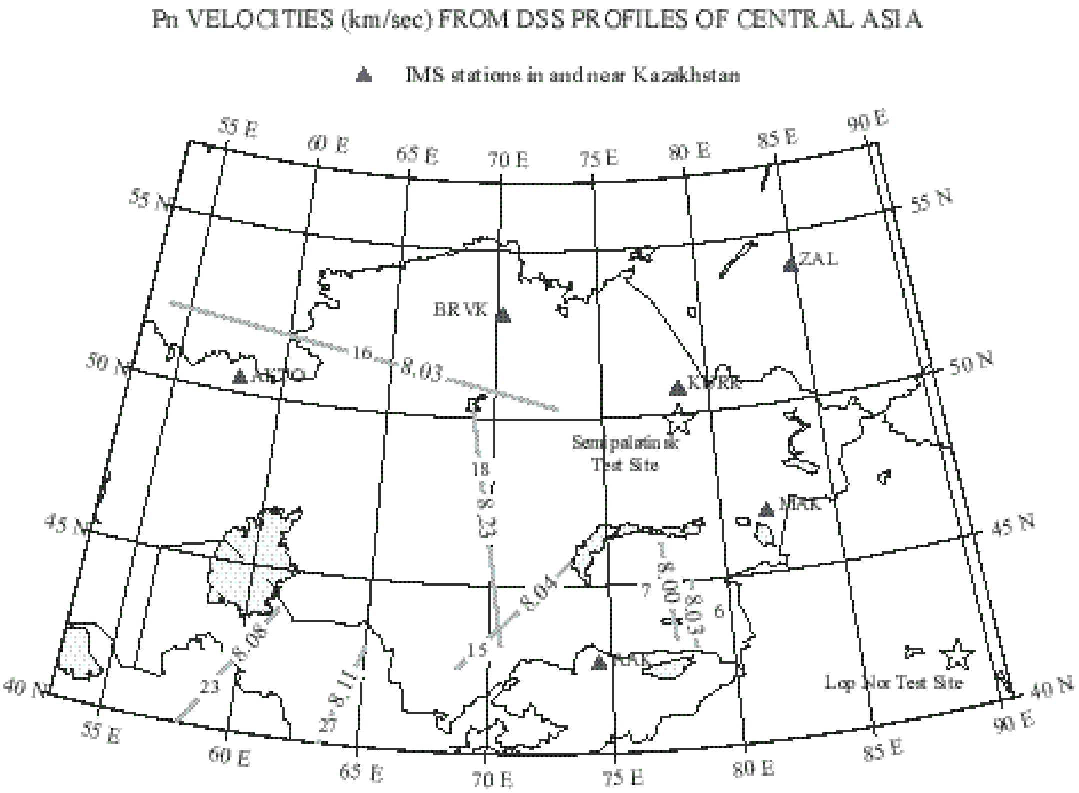

Figure 3. Phase velocities of Pn waves, for seven profiles in and near Kazakhstan.

#	Profile	Distance Range, km	Apparent velocity km/s	Time equation
6	Zhalanash-Taldykurgan	200-400	8.03	t=R/8.03 + 10.9
7	Issiksky	240-400	8.04	t=R/8.00 + 10.9
15	Aris'- Balkhash	200-520	8.04	t=R/8.04 + 9.3
16	Temir-Tau - Kuybishev	160-400	8.03	t=R/8.03 + 7.8
18	Karatay - Tengiz Lake	200-760	8.23	t=R/8.23 + 8.5
		760-880	8.63	t=R/8.63 + 13.3
23	Kopet-Dag - Aral Sea	180-600	8.08	t=R/8.08 + 8.3
27	Farab - Tamdi-Bulak	200-360	8.11	t=R/8.11 + 8.5
-	IASPEI-1991	200-900	8.11	t=R/8.11 + 7.6

Table 4. Apparent velocity of Pn waves measured from seven Deep Seismic Sounding profiles in and near Kazakhstan (see also Tables 2 and 3).

DISCUSSION

Of course we shall use much additional data in our project. This paper is only a preliminary report. Other datasets of particular relevance in calibrating IMS stations in and near Kazakhstan will include:

- arrival times of PNE signals, recorded at IMS and non-IMS stations
- arrival times of underground nuclear explosions at test sites, recorded at IMS and non-IMS stations
- arrival times of chemical explosions with known hypocenter coordinates (for example, the explosions conducted in recent years on the Semipalatinsk Test Site).
- arrival times of earthquakes whose hypocenters are know with GT5 quality, picked at IMS stations or their surrogates.

From the empirical travel time data, we expect to use more than one method to obtain source specific station corrections (SSSCs). The first method will be that described by Bondár (1999), in which our whole region (Eastern Asia) is first divided into sub-regions within each of which we shall use available information to obtain travel times as a function of distance for each of the main regional seismic phases (Pg, Pn, Sn, Lg). A preliminary such regionalization is shown in Figure 4, and the asssumption underlying this approach is that structure does not vary laterally within each sub-region. Since travel time (and hence structure) is established for each sub-region, it is conceptually possible to compute the travel time for a path from each point in Figure 4, to each of the 30 IMS stations we seek to calibrate. The correct way to obtain such a travel time, for a path that crosses one or more region boundaries, is to integrate along the actual ray path --- which in general will be laterally refracted at a region boundary so that the path does not stay in the same vertical plane. However, Bondár (1999) has suggested the following simple formula for obtaining an approximate travel time to distance X:

$$T(X) \ = \ \text{sum of } [x_i \,/\, X) \,.\, T_i\,(X)]$$

where the index i ranges over all the sub-regions crossed by the ray path, and x_i and $T_i\,(X)$ are the path length and travel t*i*me (for the full distance X) in the i-th sub-region. The desired travel time is thus obtained as a weighted average of the travel time in each sub-region, the weights being (x_i / X), the fraction of the total path in sub-region i. (A problem with this formula, is that it may be inaccurate for paths of more than 1000 km or more, in application to sub-regions smaller than 1000 km across. An artificial relation between T_i and X is then needed --- artificial, because the path length here is too long to be fully contained within the sub-region.) Once $T(X)$ is obtained, the source specific station correction (SSSC) is given by

$$T_{SSSC} = T(X) - T_{IASPEI91}$$

Additional methods for obtaining $T(X)$ from empirical travel time data include

- the development of a set of laterally-varying regional seismic velocities using tomographic methods, followed by forward calculation of travel time in the resulting three-dimensional structure; and
- the development of a purely emprical approach, in which, if enough travel time information is available, the travel time for a particular path is obtained by averaging local values directly.

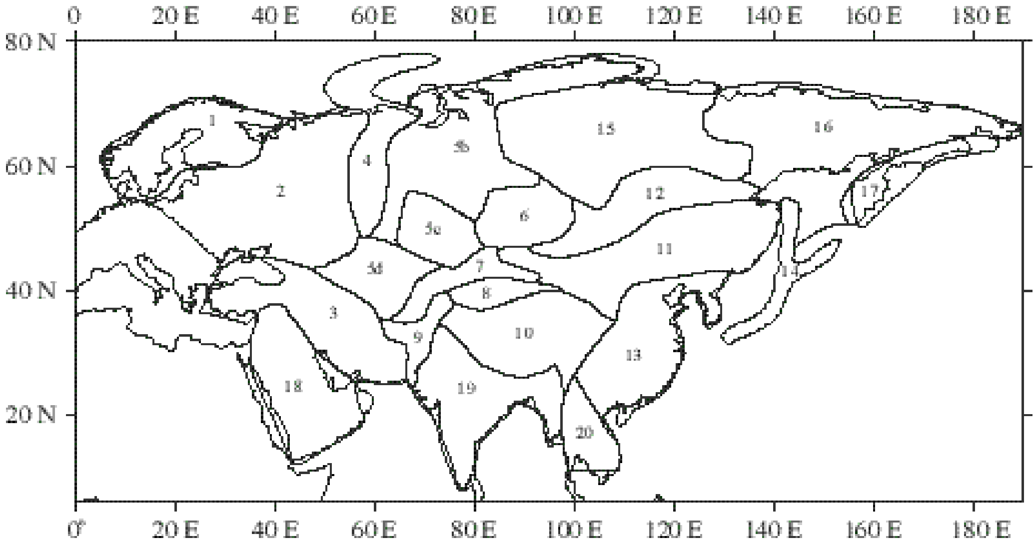

Figure 4. This map shows our preliminary regionalization of most of Eurasia, for purposes of obtaining approximate travel times of regional seismic waves to IMS station in Eastern Asia. For each regional seismic wave of interest (Pg, PN, Sn, Lg), the relationship between travel time and distance is assumed to apply throughout each sub-region.

Finally, in Tables 5 and 6 we summarize the travel-times that we are currently using to interpret regional seismic wave arrivals, for the Kazkakh Massif and the Altay-Sayan region (5c and 6 in Figure 4).

ACKNOWLEDGEMENT

Our work to calibrate the IMS stations in Eastern Asia has relied upon much data gathered by other seismologists in this region. Our future work will also depend upon the assistance of seismologists working in our area of interest.

#5c. KAZAKH MASSIF

1. Travel time for the first-arriving P wave (Pg or Pn)

R, km	Travel-Time equations
0 - 200	t(Pg) = R/6.21 + 0.8
200- 900	t(Pn) = R/8.13 + 8.4
900-1600	t(Pn) = R/8.36 + 11.4
1600-2000	t(Pn) = R/8.73 + 19.5
2000-2200	t(P) = R/9.57 + 39.6
2200-2400	t(P) = R/10.10 + 51.7
2400-2700	t(P) = R/10.95 + 70.1
2700-3400	t(P) = R/12.00 + 91.5

2. Travel time for Pg waves alone

```
50-1200 km       t(Pg) = R/6.21 + 0.8
```

3. Travel time for Sn waves

```
200-1300 km      t(Sn) = R/4.68 + 13.8
```

4. Travel time for S waves

```
1200-2000 km     t(S)  = R/5.58 + 94.7
```

5. Travel time for Lg waves

```
 200-1100 km      t(Lg) = R/3.57 + 0.50
1100-2500 km      t(Lg) = R/3.61 + 4.0
```

Table 5. Travel times for seismic waves in the Kazakh Massif.

#6. ALTAY-SAYANS REGION

1. Travel time for the first-arriving P wave (Pg or Pn)

R, km	Travel-Time equations
50-200	$t(Pg) = R/6.13 + 0.3$
200-900	$t(Pn) = R/8.13 + 8.3$
900-1600	$t(Pn) = R/8.36 + 11.3$
1600-2000	$t(Pn) = R/8.73 + 19.4$
2000-2200	$t(P) = R/9.30 + 33.4$
2200-2500	$t(P) = R/10.1 + 52.2$

2. Travel time for Pg waves alone

50 - 1200 km $t(Pg) = R/6.13 + 0.3$

3. Travel time for Sn waves

200 - 1200 km $t(Sn) = R/4.56 + 12.7$

4. Travel time for Lg waves

50 - 2000 km $t(Lg) = R/3.57 + 0.5$

Table 6. Travel times for seismic waves in the Altay-Sayans region.

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