EVENT CHARACTERIZATION USING REGIONAL SEISIMIC DATA

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ABSTRACT

This effort focuses on collecting and analyzing regional seismic data for earthquakes and underground explosions to improve seismic event characterization capabilities with regard to monitoring the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Digital data have been acquired and processed for 227 regional recordings of 148 underground nuclear explosions. Nearly 5800 regional waveforms, recorded by existing seismic stations of the International Monitoring System (IMS), for 3794 presumed earthquakes above mb 3.5 have also been processed at the prototype International Data Center (pIDC). Maximum amplitude measurements of Pn, Pg, Sn and Lg have been computed in several frequency bands ranging from 2 Hz up to 14 Hz (depending on the Nyquist frequency of a given station). The data for the presumed earthquakes have been used to estimate region-specific attenuation corrections for Pn/Sn and Pn/Lg ratios in the 2–4, 4–6, and 6–8 Hz frequency bands. Since Sn or Lg propagate more efficiently in various regions and it is difficult to map all such regions and/or paths, Pn/Smax has been tested in the event characterization analysis, where Smax = max(Sn,Lg). Distance-corrected Pn/Smax measurements from multiple regional stations are averaged for applicable events.

A hypothesis test is applied which fixes the significance level with respect to misclassifying explosions. A score for each event is computed such that events with negative scores are not screened out at the specified significance level. The significance level used here is set such that none of the available underground explosions are screened out. Events with scores greater than zero are screened out (i.e., are considered to be inconsistent with the hypothesis that the event belongs to the explosion population). Screening rates for earthquakes above mb 3.5 are compared for various regions.

Key Words: CTBT monitoring; regional seismic data; event characterization; underground explosions

OBJECTIVE

This effort focuses on collecting and analyzing regional seismic data for underground explosions and earthquakes to improve seismic event characterization capabilities with regard to monitoring the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Key aspects of this effort include: (i) acquiring regional seismic recordings for underground explosions and earthquakes; (ii) processing the waveforms to measure Pn, Pg, Sn and Lg amplitudes in various frequency bands; (iii) evaluating optimum processing techniques for regional amplitude ratios; (iv) developing a regional event-screening capability, which includes establishing necessary region-specific training sets and distance corrections; and (v) evaluating optimum screening criteria for various regions and comparing explosion and earthquake characteristics in an effort to understand how regional event characterization parameters and screening criteria can be transported to regions for which no explosion data exist.

This work is motivated by the fact that, although depth and Ms:mb are essential methods in the characterization of seismic events, the experimental depth and Ms:mb screening criteria being tested at the prototype International Data Center (pIDC) currently screen out less than 50% of the presumed earthquakes above mb 3.5 in the Reviewed Event Bulletin (REB) (e.g., Fisk et al., 1999). However, there are a significant number of events in the REB with regional seismic data that can provide additional event-screening performance. Many studies have indicated that ratios of high-frequency, regional seismic phase amplitude ratios can provide adequate separation between underground explosions and earthquakes to aid in monitoring the CTBT (see Fisk et al., 1996, and references therein).

We describe data that have been compiled and processed for 227 regional recordings of 148 underground nuclear explosions (UNE's). These explosions are compared to over 5800 regional waveforms, recorded by existing seismic stations of the International Monitoring System (IMS), for 3794 presumed earthquakes, above mb 3.5, processed at the pIDC. We then describe how region-specific distance corrections are derived and applied to Pn/Sn and Pn/Lg values in various frequency bands. To characterize the events, we use distance-corrected, network-averaged Pn/Smax in the 4–6, and 6–8 Hz bands, where Smax = max(Sn,Lg). We apply a hypothesis test to these data sets to assess whether an event is consistent with the explosion population, at a fixed significance level with respect to incorrectly screening out an explosion. A *score* is computed such that events with positive scores are screened out, i.e., are inconsistent with the hypothesis that the event belongs to the explosion population. Events with scores less than or equal to zero are not screened out. At the 0.005 significance level, none of the available explosions are screened out. We also compare the regional screening approach to that of Ms:mb and discuss some applicability issues.

RESEARCH ACCOMPLISHED

Regional Explosion Data

We have compiled 227 regional seismic recordings for 148 UNE's; some events were recorded by more than one station within 20 degrees. Table 1 summarizes our current database of regional UNE recordings. Stations that are part of the IMS network have an asterisk next to the station code. Recordings by NORES and NORSAR are for NZ events beyond regional distances (i.e., > 20 degrees) and are not used in this study. Regional amplitude measurements that have been computed for these recordings using software at the pIDC are indicated by "Yes" entries in the last column of Table 1. The regional measurements for the NTS explosions recorded by MNV and KNB were provided by LLNL (Patton and Walter, 1994) and the PNE data recorded by BRVK were provided by Jack Murphy (1998).

The processed data consist of regional phase amplitudes, Pn, Pg, Sn and Lg in the 2–4, 4–6, 6–8, and 8–10 Hz bands. Not all events have complete sets of amplitude ratios. Six of the UNE's conducted on Novaya Zemlya (NZ) were recorded by station KEV and three were recorded by ARCES. Pn/Sn was measured for these nine waveforms in all frequency bands; Pn/Lg was not measured due to Lg blockage. Five UNE's occurred at the Lop Nor test site, two recorded by ULN and BRVK, one by NIL and ZAL, one by just NIL, and one by WMQ. All amplitude ratios were computed for these events. Two chemical explosions in Kazakhstan, recorded by ZAL, and one UNE in India, recorded at NIL, also have complete data sets. Sixteen UNE's at the Balapan test site have complete data sets based on WMQ recordings. Eight additional Balapan UNE's, recorded by WMQ,

did not meet our signal-to-noise criterion (Pn-SNR > 2) and were not used in this study. There are 99 NTS explosions, 84 of which have recordings at both MNV and KNB, 8 at MNV only, and 7 at KNB only. Most of these events have Pn/Lg in the 4–6 and 6–8 Hz bands, although a few have only Pn/Lg(4–6 Hz). Last, there are 19 Peaceful Nuclear Explosions (PNE's) conducted by the Former Soviet Union with recordings by BRVK. At this time, only values of Pn/Lg(6–8 Hz) are available.

Regional Earthquake Data

Over 5800 regional waveforms that were recorded by 46 IMS seismic stations and processed at the pIDC are used in this study. These recordings correspond to 3794 distinct REB events above mb 3.5 that are presumed to be earthquakes. The restriction to mb > 3.5 is used to reduce the possibility of mining blasts contaminating the earthquake data sets. We also limit the events to those with distances beyond 3 degrees to avoid problems of distinguishing Pn and Pg, and less than 17 degrees, although regional phase amplitudes are computed at distances upto 20 degrees at the pIDC. In addition, we limit this study to data from IMS stations that have at least 20 or more recordings so that useful training sets may be formed. Accordingly, only data from 24 primary and 22 auxiliary stations are used here. Figure 1 shows the locations of the 3794 presumed earthquakes and the 148 explosions used in this study. The locations of the 46 IMS stations and 4 non-IMS stations (KEV, WMQ, BRVK and KNB) are included.

Maximum amplitudes of Pn, Pg, Sn and Lg have been measured at the pIDC in the 2–4, 4–6, 6–8, 8–10 and 10–12 Hz bands (depending on the Nyquist frequency of the instrument). For this study, we use Pn/Sn and Pn/Lg in the 4–6 and 6–8 Hz bands that satisfy the signal-to-noise criterion of Pn signal divided by pre-Pn noise greater than 2.0.

In addition to the pIDC data, the earthquake data set also includes 60 recordings by MNV and 75 by KNB of Pn/Lg in the 4–6 and 6–8 Hz bands for earthquakes near NTS, processed by LLNL in the same way as the 99 UNE's. These earthquakes are necessary to properly calibrate stations MNV and KNB.

Table 1: Summary of Regional Underground Nuclear Explosion Data

Station	Distance	Magnitude	Test Site	Explosion Dates	Processed?
KEV	9.4 3.1-19.5	5.52–5.90 4.70-5.50	NZ PNE's	821011, 841025, 870802, 880507, 881204, 901024 5 (820904-850718)	Geotool
ARCES*	9.9	5.60–5.90	NZ	880507, 881204, 901024	ISEIS
NORES	20.4	5.60-5.90	NZ	841025, 870802, 880507, 881204, 901024	No
NORSAR*	20.5	3.80-6.04	NZ	761020, 771009, 840826	No
ZAL*	12.2 6.2, 6.0	4.71 3.95, 3.80	Lop Nor Kazakhstan	960729 970803, 980822	Yes Yes
NIL*	14.5 6.7	5.69, 4.71 5.00	Lop Nor India	960608, 960729 980511	Yes Yes
ULN*	14.3	5.73, 5.54	Lop Nor	950515, 950817	Yes
WMQ	8.6 2.2	4.6–6.1 4.7	Balapan Lop Nor	21 (1987-1989) 880929	Yes
BRVK	17.0 7.2-17.2	5.73, 5,54 4.5-5.8	Lop Nor PNE's	950515, 950817 19 (730815-880906)	No
MNV*	1.7–2.2	2.4–5.5	NTS	92 Explosions	LLNL
KNB	2.5–2.8	2.6–5.5	NTS	91 Explosions	LLNL

Distance Corrections

The unequal rates of attenuation with distance between regional P and S phases necessitates a correction for distance if amplitude ratios recorded at different distances are to be compared (see Sereno, 1990, Bottone et al., 1997, and Fisk et al., 1998). Figure 2 plots Pn/Lg(6–8 Hz) values as a function of distance from the recording station for the REB events and explosions worldwide (the BRVK PNE data have been excluded here, but will be considered below). The P/S distance dependence is modeled by a three-parameter equation of the form

$$\log(P/S) = \alpha + \beta \log(\Delta/\Delta_0) + \gamma\Delta \qquad (1)$$

where α, β, and γ are parameters depending on the particular amplitude ratio (Pn/Lg or Pn/Sn) and the frequency band, is the epicentral distance, and the constant Δ_0 is a reference distance that is set at 1500 km, roughly the mean epicentral distance of the all REB regional events.

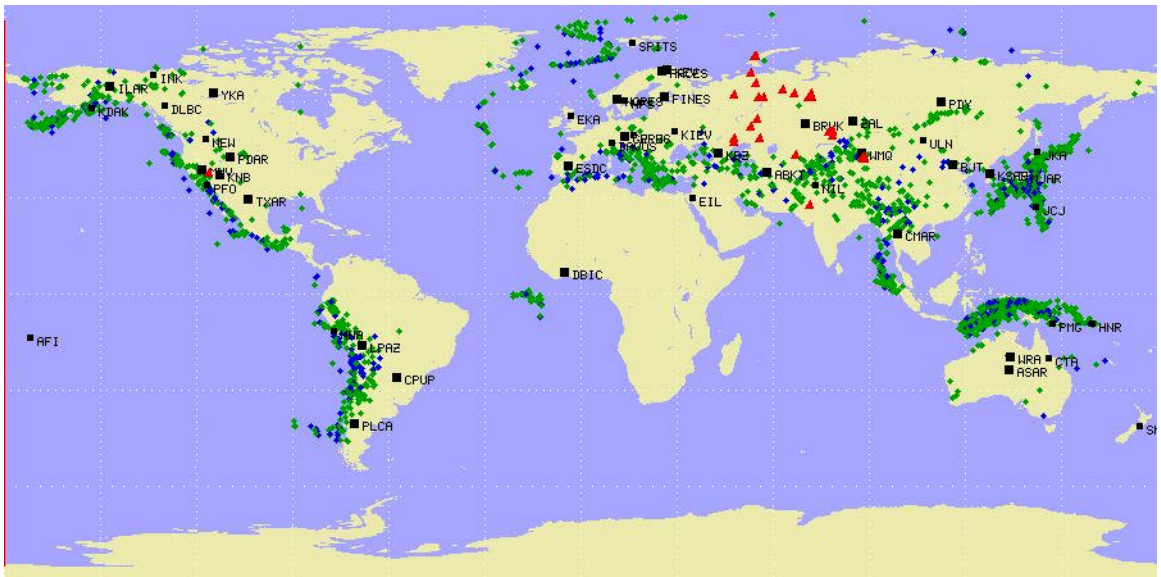

Figure 1. Locations of 148 nuclear explosions (triangles) and 3794 REB earthquakes with mb 3.5 and above. Locations of 46 IMS stations and 4 stations with explosion recordings (KEV, WMQ, BRVK, and KNB) are also shown.

Equation (1) is represented by the solid curve in Figure 2, with the three parameters estimated to minimize the sum of the squared residuals of the REB data points from the curve. It is clear from the plot that if this amplitude ratio for the explosions recorded at MNV and KNB, which have propagation paths only 200 to 300 km in length, are to show separation from the entire sample of all REB events at all distances, then distance corrections will be necessary. In general, amplitude ratios at short distances, 200–500 km, have smaller P/S ratios for both explosions and earthquakes, as demonstrated in Figure 2, and, therefore, distance corrections are most important at these distances.

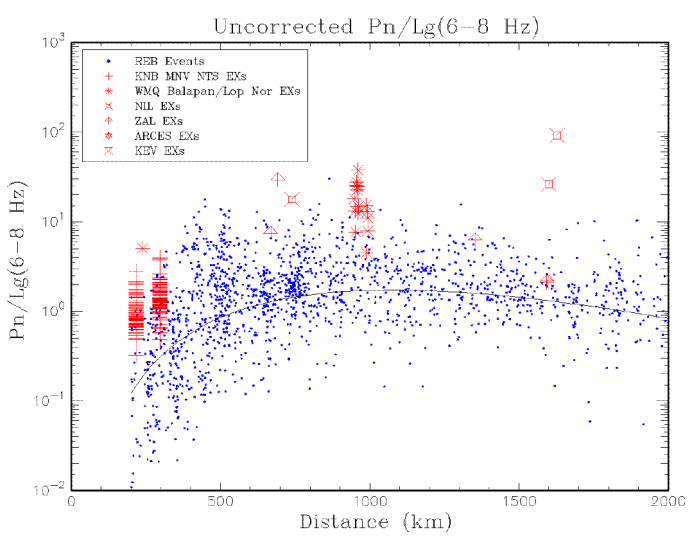

Figure 2. Uncorrected Pn/Lg(6–8 Hz) versus distance for all REB events and explosions worldwide. The solid curve is a best-fit, three-parameter estimate of the distance dependence.

While Figure 2 indicates the general distance dependence of regional amplitude ratios, it is necessary to estimate distance corrections for each station to account for region-specific variations in attenuation. We have investigated several ways of computing distance corrections for a given region and station. We have found that the overall event-screening results are not sensitive to which method is used. The approach we adopt in the remainder of this paper follows Jenkins et al. (1998), in which we divide the world into eleven tectonic regions and estimate b and g in each region using all data available in that region. For each station in a particular tectonic region, a is then estimated using data from that station only. Thus, the distance-correction curves for each station in the same tectonic region have the same shape, but are adjusted to best fit the mean of the data for that station. In our study, two of the regions, eastern North America and Africa, have inadequate data to compute distance corrections, leaving nine regions.

An example of the distance corrections is shown in Figure 3, where Pn/Lg and Pn/Sn values in the 4–6 and 6–8 Hz bands are plotted versus distance for ZAL in the central Asia region. The solid line is the distance-correction curve fit to the ZAL earthquake data. For comparison, the dashed curve is the worldwide-average curve. For ZAL, the two sets of curves are fairly similar. Also plotted are the values of the P/S amplitude ratios for three explosions recorded by ZAL. These three events are clearly separated from the earthquakes. This separation will be quantified below.

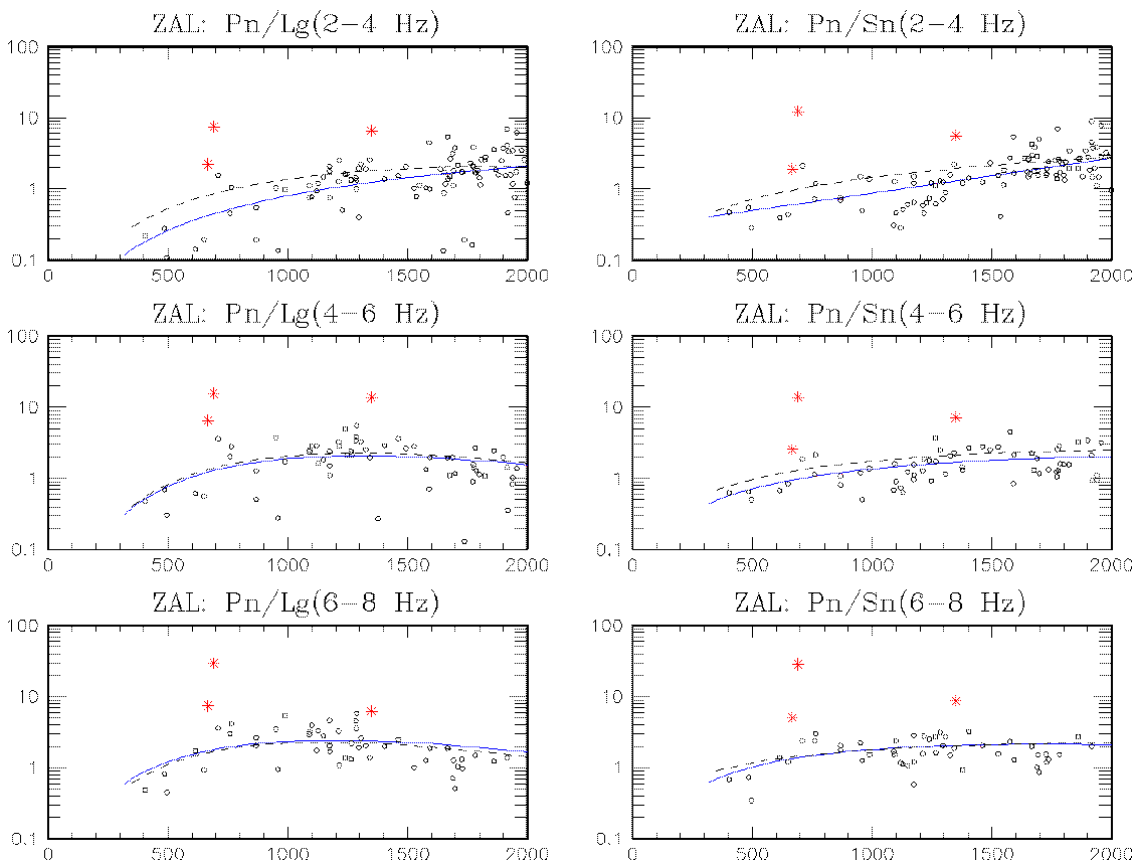

Figure 3. Regional P/S versus distance (km) at ZAL. The solid lines are the distance-correction curves.

Event Characterization Parameters

Pn/Lg and Pn/Sn amplitude ratios are computed, using the same frequency band for the P and S wave amplitude measurements (to minimize source size effects). A problem with using all combinations of the P/S values is that Lg or Sn are severely attenuated or blocked for some paths. For example, Lg is typically blocked along many oceanic or other thin crustal paths and Sn is severely attenuated in the western U.S. and the Middle East. Since

it is difficult to map all such paths, we use Pn/Smax values (in each frequency band), where Smax is the maximum of Lg and Sn (i.e., Smax is the Lg or Sn phase which propagates more efficiently in a given region).

Higher frequency bands generally provide better separation between explosion and earthquake populations (e.g., Fisk et al., 1996; Kim et al., 1997; Walter et al., 1995). However, signals at frequencies above 8 Hz are often below noise levels. We have found that the best overall performance of the hypothesis test presented below is provided by using the 4–6 and 6–8 Hz bands. Thus, we use two event characterization parameters, distance-corrected log[Pn/Smax(4–6 Hz)] and log[Pn/Smax(6–8 Hz)]. Taking the logarithm of each amplitude ratio usually results in populations that are more normally distributed (Bottone et al., 1997), allowing a simpler statistical treatment.

Of the nearly 3800 regional events recorded at 46 IMS stations used in this study, about 25% of these events have regional data recorded at more than one station. About 7% of the events are observed at three or more stations. Our current treatment is to average the regional measurements for those events with multi-station data. We have found that network averaging provides good screening performance, without screening out any explosions, but may not necessarily be the best approach for combining multi-station data. We plan to investigate this problem further. Averaging is performed on the distance-corrected values of log(P/S) for each type of amplitude ratio. If a particular amplitude ratio is missing (e.g., due to low signal-to-noise), it is not included in the averaging.

Figure 4 is a plot of Pn/Smax(6–8 Hz) versus distance after distance corrections and network averaging have been performed. The legend associates the marker types with the various events. It can be seen that the majority (about 80%) of the Pn/Smax(6-8 Hz) values for the REB earthquakes are below the lowest value for the explosions.

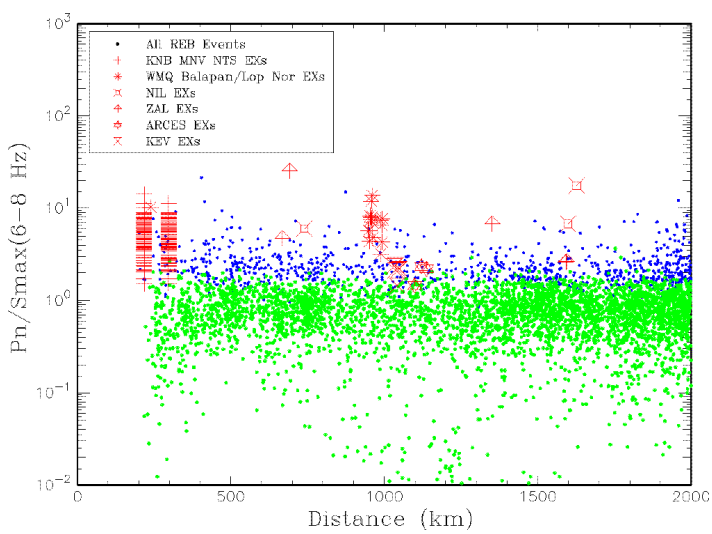

Figure 4. Pn/Smax(6–8 Hz) versus distance after applying distance corrections and network averaging.

Experimental Event-Screening Criterion and Score

A screening criterion may be defined as a hypothesis test, based on a linear discriminant function (see Anderson, 1984), with a fixed significance level with respect to incorrectly screening out an explosion. More precisely, let
$\mathbf{x} = (x_1, x_2)'$, where x_1 and x_2 are the distant-corrected, network-averaged values of log[Pn/Smax(4–6 Hz)] and log[Pn/Smax(6–8 Hz)]. Assuming the data have normal distributions and the covariance matrices for the explosions and earthquakes are equal, the optimal linear combination of x_1 and x_2 is given by

$$\lambda = (\mathbf{u}_{EX} - \mathbf{u}_{EQ})'\Sigma^{-1}\mathrm{x}, \qquad (2)$$

where $\mathbf{u}_{EX}$ and $\mathbf{u}_{EQ}$ are the vector means of $\mathbf{x}$ for the explosion and earthquake populations, respectively, and Σ is the covariance matrix. Under the null hypothesis that $\mathbf{x}$ is an element of the explosion population, λ is also normally distributed with mean u_λ and $\sigma_\lambda^2 =$ variance, where

$$u\lambda = (\mathbf{u}_{EX} - \mathbf{u}_{EQ})' \Sigma^{-1} \mathbf{u}_{EX} \tag{3}$$

and

$$\sigma_\lambda^2 = (\mathbf{u}_{EX} - \mathbf{u}_{EQ})' \Sigma^{-1} (\mathbf{u}_{EX} - \mathbf{u}_{EQ}) \tag{4}$$

We define a screening criterion, to fix the probability of screening out an explosion to be a, given by

$$\lambda < u_\lambda - z_\alpha \sigma_\lambda, \tag{5}$$

where z_α is the (1–α)-percentile of the standard normal distribution with zero mean and unit variance. A *score* may be defined such that an event is screened out at the α significance level, if the score is greater than zero:

$$\text{Score} = \frac{u_\lambda - \lambda}{z_\alpha \sigma_\lambda} - 1. \tag{6}$$

Unbiased sample estimates of the means and covariance matrix are computed from the explosion and earthquake data sets described above and are used in Equations (2)–(6).

The scores for 129 explosions and 3794 earthquakes are represented by the histograms in Figure 5. The significance level, α, is chosen to be 0.005, corresponding to $z_\alpha = 2.576$. In this case, the scores for all the explosions are less than zero and, thus, none are screened out. Typically we should expect one out of 200 explosions to be screened out at this significance level. About 79% of the earthquakes have scores greater than zero and, thus, would be screened out. This gives an estimate of the power of the test, which is the probability that an earthquake will be screened out.

In cases where one of the two discriminants is not available the test described above based on a single frequency band is applied. In this case, the explosion error will still be the same, approximately 0.005, however, the probability of screening out earthquakes will change, depending on which event characterization parameter is available and the relative separation of the explosion and earthquake populations in that case.

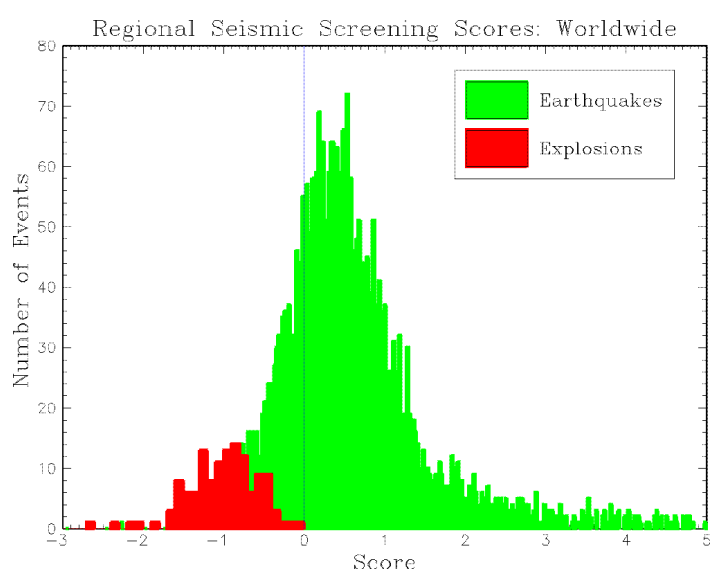

Figure 5. Histograms of regional screening scores for 129 explosions (left) and 3794 earthquakes (right).

None of the explosions are screened out (all have scores less than zero using a significance level of 0.005), while 79% of the REB earthquakes are screened out (scores greater than zero).

Comparison to Ms:mb

The difference of body and surface wave magnitudes (Ms:mb) has long been used to characterize seismic events. In the current implementation at the pIDC, a seismic event above mb 3.5 and having an Ms measurement is screened out if the 97.5% confidence interval of 1.25mb–Ms is less than 2.2 (Fisk et al., 1999). There are a number of similarities between the Ms:mb and regional event-screening criteria. Both procedures utilize the difference of the logarithm of seismic amplitudes measured in appropriate frequency bands. Distance corrections are required for both methods. In addition, the regional variation for distance-corrected Pn/Lg between NTS and Balapan events is similar to that of Ms:mb. The regional and Ms:mb screening criteria are both defined empirically so that no available explosions are screened out. Figure 6 indicates that the performance of the regional and Ms:mb screening criteria are similar. On the left is a plot of the regional score, scaled to the original values of log(Pn/Smax), versus mb for the regional events. The plot on the right shows 1.25mb–Ms versus mb for a similar sets of events. In each case, the percentage of REB earthquakes screened out is about 80%, while no explosions are screened out.

While there is some theoretical basis for the ability of regional P/S to characterize seismic events, it is not as firm as for Ms:mb. Regional phases usually exhibit greater sensitivity to path variations as well. For these reasons, among others, Ms:mb is generally more reliable. However, there are many events of interest which do not have Ms and, thus, the Ms:mb screening criterion cannot be applied. In particular, none of the explosions below mb 4.5 in our data sets have Ms measurements, while many of these events have regional data, allowing the regional screening analysis to be applied. In fact, about 70% of the events in the REB with useful regional phases do not have Ms:mb.

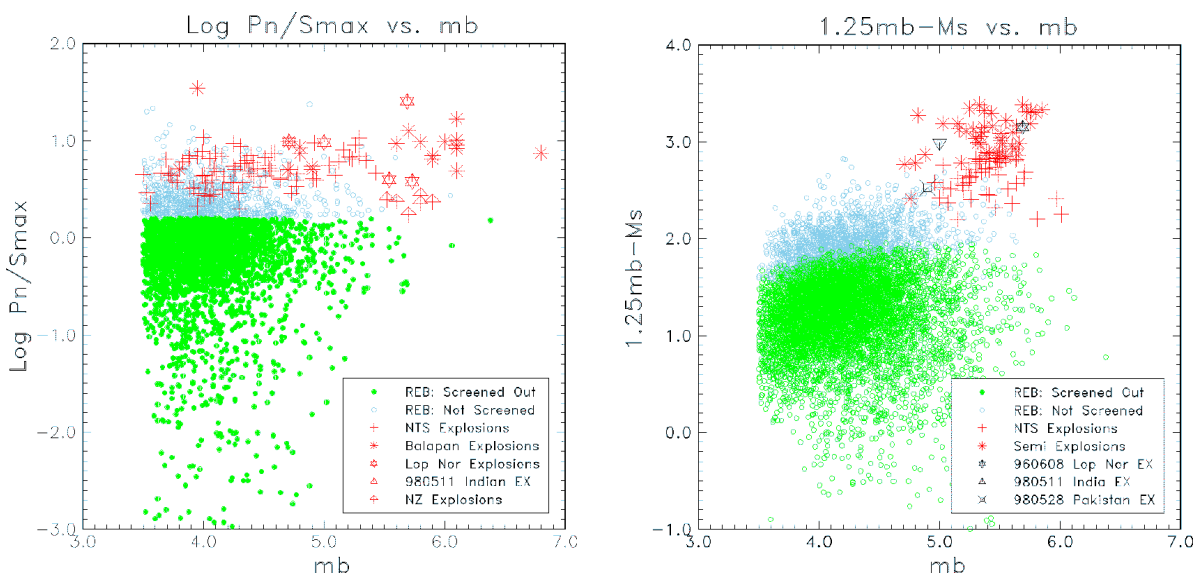

Figure 6. Comparison of the regional Pn/Smax (left) and Ms:mb (right) screening criteria versus mb. In both cases, no explosions are screened out while about 80% of the REB earthquakes are screened out.

Borovoye Data

The 19 Soviet PNE's recorded by Borovoye (BRVK) were not included in our analyses because only Pn/Lg values in the 6–8 Hz band are currently available. For the analysis to be consistent, Pn/Sn is also needed because earthquake data recorded by BRVK suggests that Smax is Sn. Also, having P/S in the 4–6 Hz band usually improves the screening performance. Although using Smax can only reduce the Pn/Smax ratio for the PNE's, there may be an even larger reduction for the earthquakes. This can only be determined with consistent

measurements of all available waveforms. Nevertheless, there appear to be one to three problematic explosions in the BRVK data set.

Figure 7 is similar to Figure 2, showing a plot of Pn/Lg(6–8 Hz) versus distance, with the 19 PNE's included. There is one PNE at about 1200 km from BRVK whose Pn/Lg(6–8 Hz) value is below the distance-correction curve. If Pn/Lg(6–8 Hz) were the only feature and only events with Pn/Lg(6–8 Hz) less than this PNE could be screened out, then the screening rate for earthquakes would be less than 50%. Two other events, at about 800 km and 1200 km, are barely above the distance-correction curve and could also present difficulties. All three events are located north of the BRVK, where there are virtually no earthquake data to compare to the PNE's.

Figure 8 shows plots of Pn/Lg(6–8 Hz) on the left and Pn/Sn(6–8 Hz) on the right versus distance for 18 earthquakes, two Lop Nor UNE's, and the 19 PNE's (Pn/Lg(6–8 Hz) only) recorded by BRVK. Distance-correction curves (solid lines) that were fit to the 18 earthquakes are included in each plot. For comparison, the average distance-dependence curves for central Asia are also plotted (dashed lines). Note that the fit to the BRVK Pn/Lg data is much higher than the central Asia curve, indicating that earthquakes recorded by BRVK typically have values of Pn/Lg above the central Asia average, while the fit to the BRVK Pn/Sn data is lower than the central Asia curve. Note also that for the two Lop Nor explosions, for which there are both Pn/Lg and Pn/Sn, the values of Pn/Sn are further above the distance-correction curve than is the case for Pn/Lg. Neither of these Lop Nor UNE's were screened out using the regional screening procedure. This example indicates the need for a full evaluation of this BRVK PNE data.

Applicability Issues

Although none of the available explosions at the Nevada, Lop Nor, Balapan, Indian and Novaya Zemlya test sites were screened out, as shown in Figure 5, it should be emphasized that the effectiveness of this experimental procedure is unknown for regions without calibration data. For example, northern Russia is relatively aseismic. The PNE data recorded by BRVK indicate possible difficulties in such aseismic regions. Although none of the six NZ underground nuclear explosions were screened out, calibration data are limited in this region.

It should also be noted that all explosions used in this study were underground. Some actual and simulated examples of in-water explosions indicate that they may generate relatively large S waves (e.g., Baumgardt and Der, 1998), depending on the boundary condition at the liquid/solid interface, which would reduce the effectiveness of the current screening procedure. Thus, the regional screening criterion cannot be applied confidently to offshore events at this time. Note that by restricting the procedure to onshore events above mb 3.5, it would not be applied to any of the events in the Novaya Zemlya region since 1990. In the future, it may be possible to combine regional seismic data with other seismic and hydroacoustic characteristics to develop a useful screening procedure for offshore events.

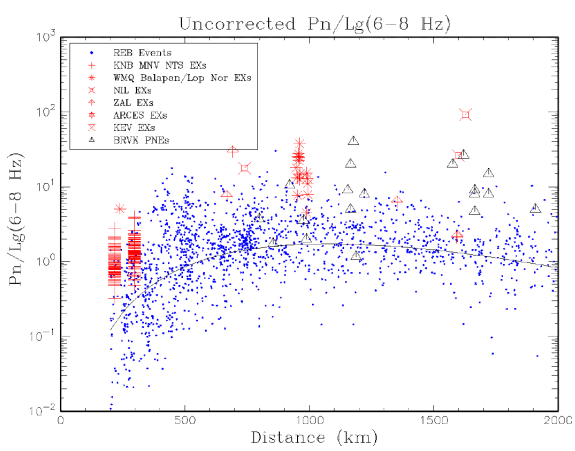

Figure 7. Uncorrected Pn/Lg(6–8 Hz) versus distance for REB events and explosions worldwide, including 19 Soviet PNE's.

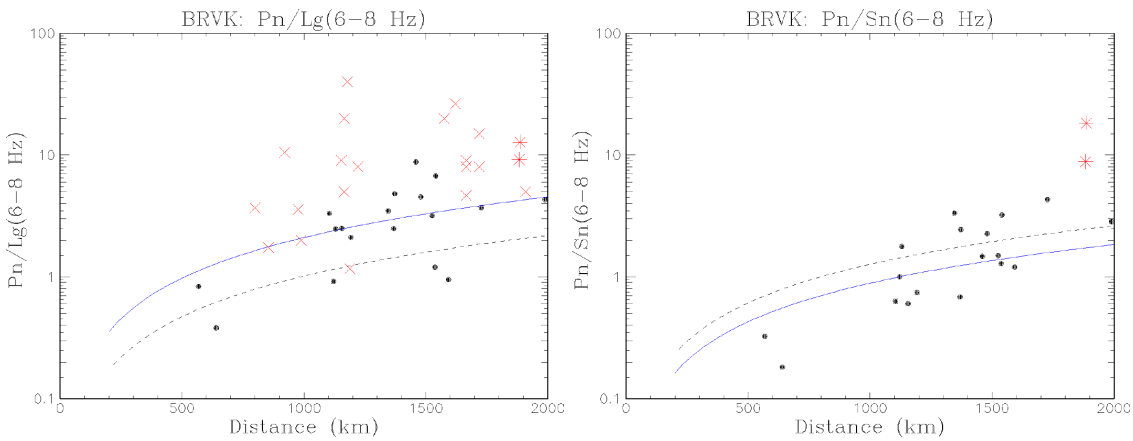

Figure 8. Pn/Lg(6–8 Hz) and Pn/Sn(6–8 Hz) values versus distance for BRVK. Solid lines represent best-fit distance-correction curves for BRVK; dashed lines indicate the average central Asia curves.

CONCLUSIONS AND RECOMMENDATIONS

High-frequency, regional seismic P/S amplitude ratios have potential utility to augment the seismic event-screening procedures based on event depth and Ms:mb. Using the screening procedure described in this paper, no available underground explosions were screened out at the Nevada, Lop Nor, Balapan, Kazakhstan, Indian, or Novaya Zemlya test sites, while about 79% of onshore REB events above mb 3.5 and with Pn-SNR > 2.0 can be screened out. This screening performance compares favorably with that of Ms:mb. The experimental depth and Ms:mb screening criteria at the pIDC currently screen out less than 50% of REB events above mb 3.5 and about 70% of REB events that have applicable regional data are relatively shallow and do not have an Ms measurement.

One to three of the 19 PNE's recorded by BRVK indicate potential difficulties with applying the procedure to regions with insufficient calibration data. Additional BRVK data are needed to complete this evaluation. A possible approach to treating aseismic regions, such as northern Russia where these PNE's were located, is to simply not apply the regional screening criterion in such regions where the performance is uncertain. Since there are few events to consider in aseismic regions, the overall screening rate of earthquakes would not be significantly affected.

In addition to regions without adequate calibration data, screening performance for offshore events is also uncertain. All of the explosions in this study were conducted underground and some evidence suggests that in-water events may generate relatively large S-wave amplitudes, adding to the uncertainty of applying the regional screening procedure to such events. This issue should be investigated further. In the future it may be possible to combine the regional seismic data with other seismic and hydroacoustic characteristics to develop a useful screening procedure for offshore events.

There are several potential ways to improve the regional screening performance. Currently, the pIDC measures regional phase amplitudes only on vertical components. Although P/S ratios measured on vertical components show reasonable power for separating earthquakes from explosions, Kim et al. (1997) showed that P/S spectral ratios of rotated, three-component (3-C) records improve the power. Since most IMS seismic stations have 3-C broadband sensors, the horizontal components should also be considered for event characterization. Also, a small percentage of the automatic regional phase amplitudes measurements suffer from poor data quality (e.g., noise spikes, clipping, drop-outs). Improved methods of flagging such data are needed. Difficulties measuring regional phase amplitudes also exist for events recorded at distances less than about 3 degrees, and so have not been used in this study. More careful analysis at these near regional distances is necessary so that the screening procedure can be applied to these, potentially important, events. Processing additional explosion data, including the BRVK PNE data, should help improve the calibration of corresponding regions. Complicated geological regions may need to be divided into subregions to improve the performance of the procedure.

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