Detection and Identification of Small Regional Seismic Events

T. J. Bennett, B. W. Barker, M. E. Marshall, and J. R. Murphy
S-CUBED
11800 Sunrise Valley Dr., Suite 1212
Reston, Virginia 22091

Contract No. F 19628-93-C-0093
Sponsored by ARPA

Abstract

Many seismic events detected and located by the prototype International Data Center (IDC) at the Center for Monitoring Research (CMR) are small regional events. However, only very limited experience exists for regional seismic signals from small or decoupled nuclear explosions, which would be important in a CTBT monitoring environment. Furthermore, many of the events currently being reported by the IDC occur in geographical regions for which there is little or no previous seismic monitoring experience with underground nuclear explosion tests. The goal of this research has been to enhance the experience base for the IDC and to identify potential techniques and limitations of IDC seismic monitoring at the low magnitude levels appropriate to a CTBT.

For these investigations we have focussed primarily on application of theoretical source scaling methods to the regional signals from observed underground nuclear explosions and, then, compared the behavior of the scaled regional signals to that from other source types with similar, small magnitudes. During the initial stages of this project, a test database of underground nuclear explosion tests recorded at the Fennoscandian regional arrays was identified. Mueller-Murphy theoretical source scaling was used to scale the array records down to the levels appropriate to CTBT monitoring goals (e.g. 1-kt fully decoupled), and the scaled signals were re-embedded into normal background noise conditions. A copy of this scaled explosion database was provided to CMR for testing capabilities of the existing system, and we performed some independent signal analysis procedures on the waveforms to discern features which could be relevant in identification monitoring at the IDC. In a separate study under this contract, we also investigated seismic identification techniques for some specific events recently detected by the IDC. One such event was the January 5, 1995 seismic event in the central Ural mountains of Russia which had a magnitude of 4.4. Comparisons of L_g/P or S/P ratios and M_S-vs-m_b at selected stations seem to indicate that this event was probably a rockburst or mine tremor.

Key Words: Seismic, Discrimination, Regional, Scandinavia, Explosion, Decoupling, Array.

Objective

Monitoring seismic events at the low magnitude levels appropriate to a CTBT will require the utilization of detection and identification techniques based on observations at regional stations. It will also require extension of discrimination methodology from specific regions within which the regional techniques have been established into new areas which will require calibration. The prototype International Data Center (IDC) at the Center for Monitoring Research (CMR) is routinely detecting and locating seismic events throughout the world as part of the GSETT-3 experiment. Many of the reported events are small and occur in regions where there is little or no direct experience with observations from underground nuclear explosions. Even where such nuclear explosion experience does exist, it is generally for events with magnitudes well above those of most events being reported by IDC. As a result it is difficult to assess potential identification techniques and limitations of IDC seismic monitoring in the context of a CTBT. The primary objective of this investigation has been to make some preliminary attempts to simulate the behavior of regional signals from underground nuclear explosion tests down at the levels of interest for CTBT monitoring (e.g. 1-kt fully decoupled). To accomplish this objective we applied Mueller-Murphy source scaling theory to signals observed at Fennoscandian regional arrays for larger nuclear explosions and then reintroduced the scaled-down signals into the normal seismic background noise. Copies of these simulated nuclear explosion signals were provided to the CMR for testing IDC algorithms, and additional independent studies of the regional signals were conducted to assess potential limitations on detection and identification techniques. A secondary objective of this project has been to investigate seismic characteristics of some specific events reported by the IDC. We have looked at IDC data from selected seismic events and attempted to determine regional signal characteristics which would be useful for identification.

Research Accomplished

At last year's research review meeting, we described the procedures which we have been using to scale regional seismograms from larger nuclear explosions to simulate small and decoupled nuclear tests. The procedures are somewhat similar to the magnitude scaling performed by Kvaerna (1992) to investigate detection threshold monitoring in the vicinity of the Russian test site at Novaya Zemlya (NZ) except we use the more elaborate explosion source scaling theory of Mueller and Murphy (1971). Instead of the simple amplitude reduction produced by magnitude scaling, the explosion source scaling theory produces a combined amplitude reduction and shift to higher frequencies in scaling to lower yield explosions. This scaling operation is represented in the frequency domain as

$$\frac{S_2(\omega)}{S_1(\omega)} = \frac{p_2(\omega)\, r_{el2}}{p_1(\omega)\, r_{el1}} \, \frac{\omega_{o1}^2 + i\,\omega_{o1}\,\omega - \beta\,\omega^2}{\omega_{o2}^2 + i\,\omega_{o2}\,\omega - \beta\,\omega^2}$$

where r_{el1} and r_{el2} are the elastic radii of the two sources at which the spherically symmetric pressures $p_1(\omega)$ and $p_2(\omega)$ act and

$$\omega_{oi} = \frac{\alpha}{r_{el_i}} \quad \text{and} \quad \beta = \frac{\lambda + 2\,\mu}{4\,\mu}$$

with α the P-wave velocity and λ and μ the Lame constants characteristic of the source medium.

We have applied this scaling operation to the seismic records measured at the Fennoscandian regional arrays (viz. ARCESS, FINESS, NORESS) from three large underground nuclear explosions (two at NZ and one PNE north of Arkhangel'sk and east of the White Sea, cf. Figure 1). NORESS was the only operating regional array at the time of the latter event. The NZ explosions both had magnitudes of 5.7 m_b, and the magnitude of the PNE was 5.0 m_b. The epicentral distances from the NZ explosions were approximately 2260 km to NORESS, 1100 km to ARCESS, and 1770 km to FINESS; and the epicentral distance from the PNE to NORESS was 1560 km. So, the recording distances can generally be described as far regional.

Figure 2 shows the source scaling factor as a function of frequency for explosions of four different yields relative to a large explosion. In this case the large explosion has an elastic radius of 685 m corresponding approximately to a yield of 50 kt which is roughly equivalent in magnitude to 5.7 m_b, the magnitude of the NZ explosions. The elastic radii associated with the various scale factors (viz. 186 m, 97 m, 77m and 45 m) correspond approximately to explosion yields of 1-kt fully tamped, 10-kt fully decoupled, 5-kt fully decoupled and 1-kt fully decoupled, respectively. It can be seen from Figure 2 that the theory predicts significant reductions in amplitude for the smaller events. The amplitude reductions are predicted to be much larger at frequencies below about 1 Hz than at high frequencies. The scale factor shows a transition between about 1 Hz, which corresponds to a corner controlled by the larger event being scaled, and a high-frequency corner, which corresponds to and varies with the yield or elastic radius of the smaller event. Comparing the low-frequency levels of the scale factors for 1-kt fully tamped (r_{el} = 186 m) and 1-kt fully decoupled (r_{el} = 45 m), we note the difference is a factor of 70, corresponding to the maximum decoupling factor seen in empirical observations.

In last year's review presentation and in our subsequent report (cf. Bennett et al., 1994), we described in detail and illustrated the steps in the simulation process. After scaling, the modified signals were superimposed on long noise records for each of the arrays. The noise samples used were selected at the time because they seemed to represent some of the longer record segments available which had no apparent signals; subsequently longer noise segments can now be easily accessed in the IDC database for more recent time periods. In our previous presentation we noted that the signals at all three arrays for the 1-kt fully decoupled explosion at distances corresponding to NZ were buried in noise on the broadband records and not apparent. However, we found that at the nearest station (viz. ARCESS at $R \approx 1100$ km) the regional signals at high frequencies could be brought out of the noise by bandpass filtering. This is illustrated in Figure 3 where we show a narrow bandpass filter analysis of the vertical-component record simulating a 1-kt fully decoupled explosion from NZ recorded at ARA0 (using in this case the noise from 04/23/92). The analysis shows little evidence of the regional signals at frequencies below 3 Hz, but strong signals in the 3 Hz to 20 Hz bands. It is apparent from these analyses that most reliable regional methods for detection, location, and discrimination of small or

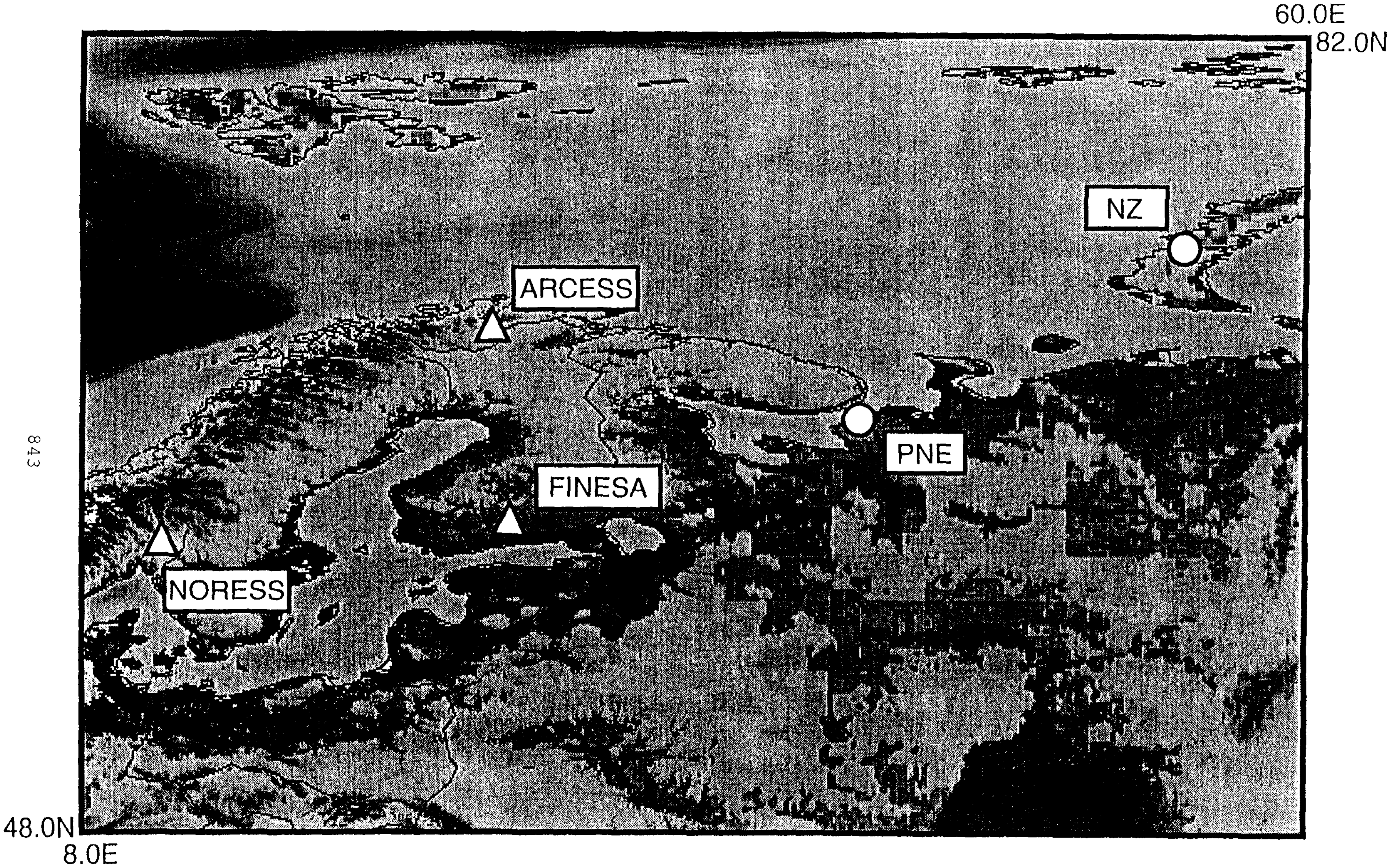

Figure 1. Locations of nuclear explosion sources and ARPA regional array stations.

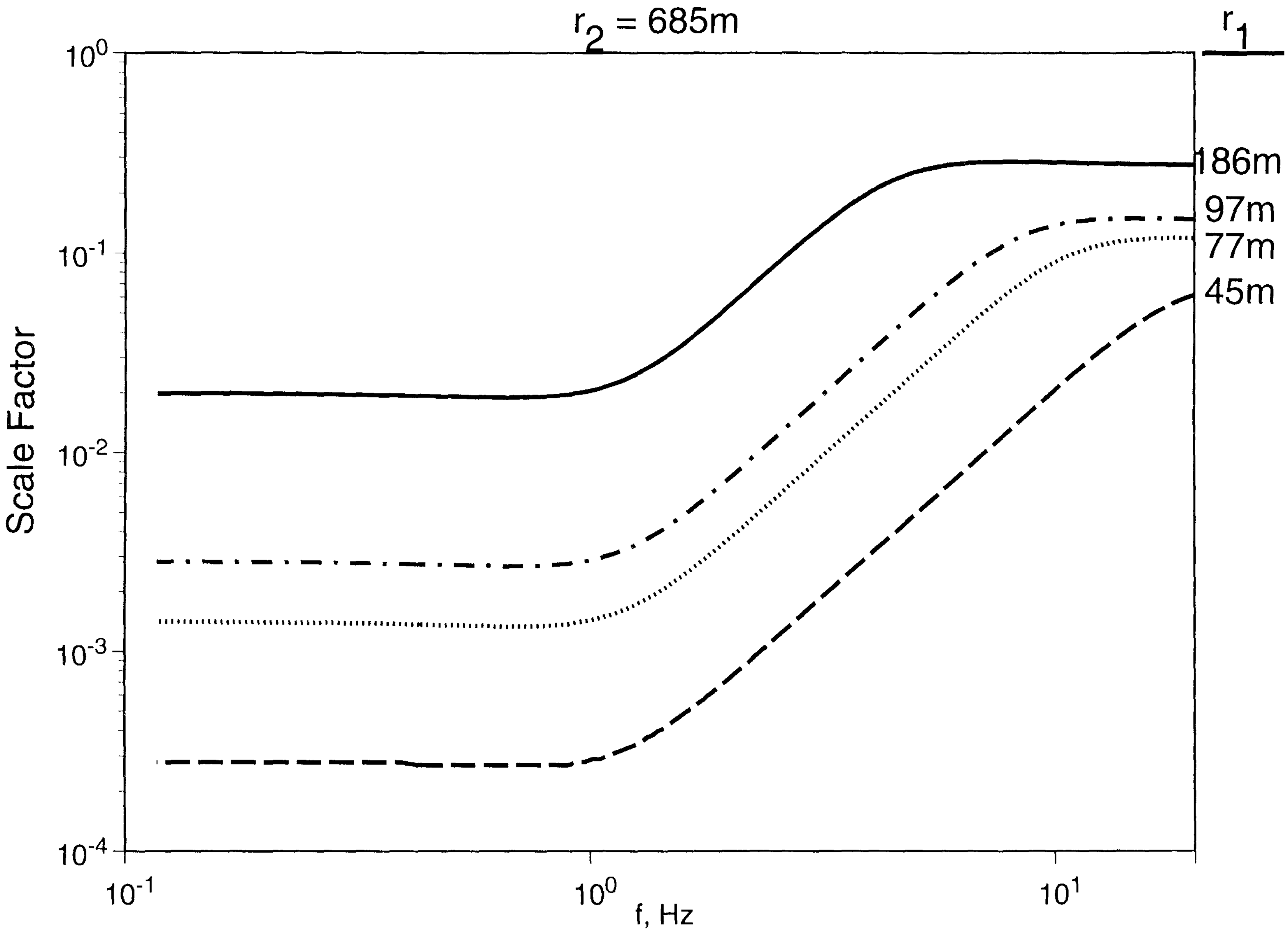

Figure 2. Source scaling factor as a function of frequency for explosions of different yields characterized by their elastic radii (r_1) relative to a larger explosion with an elastic radius of 685m (r_2).

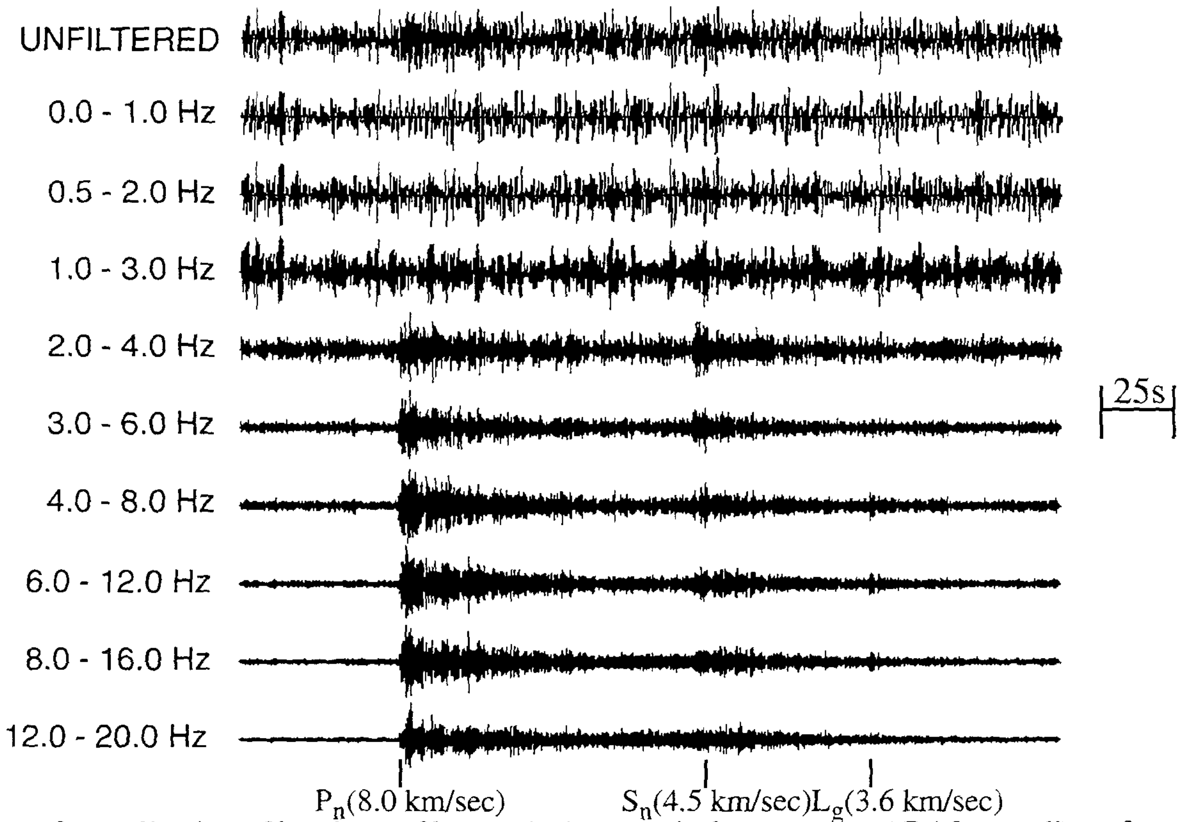

Figure 3. Application of band-pass filter analysis to vertical-component ARA0 recording of the 10/24/90 NZ explosion scaled down to 1kt fully decoupled.

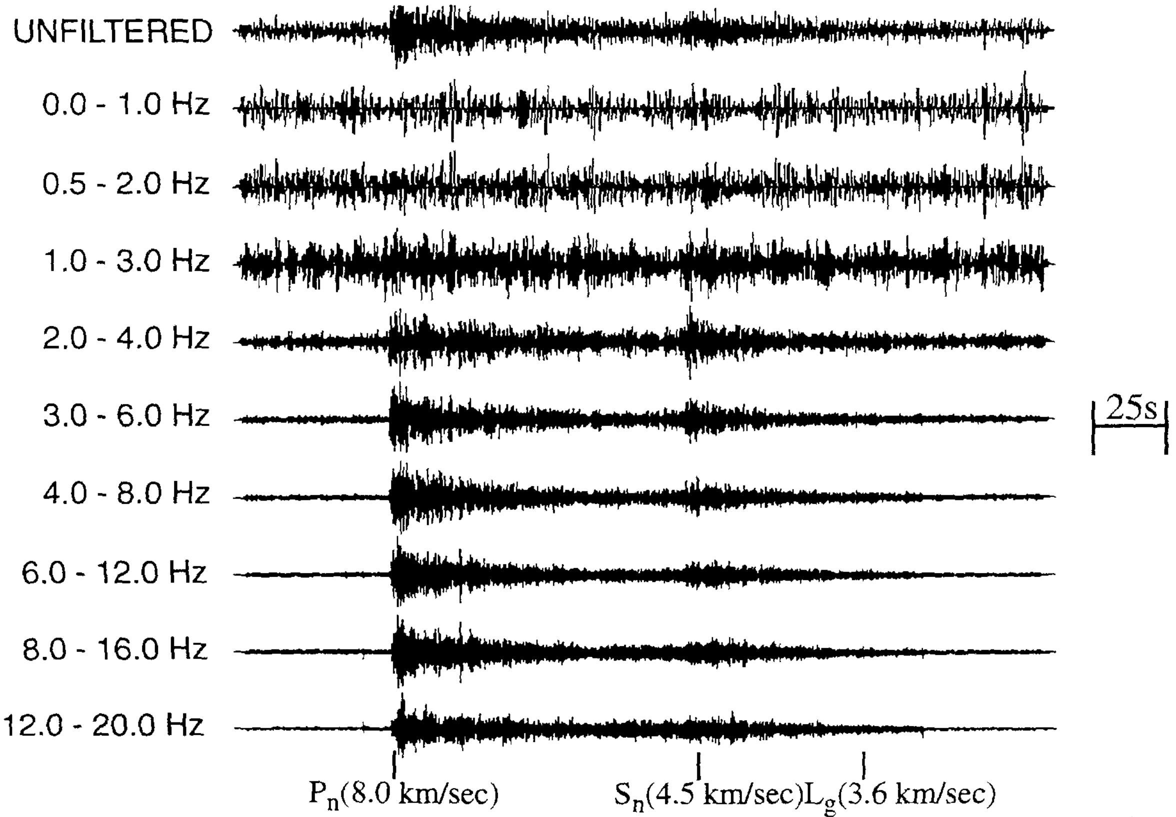

Figure 4. Application of band-pass filter analysis to vertical-component ARA0 recording of the 10/24/90 NZ explosion scaled down to 1kt fully decoupled.

decoupled nuclear explosion tests will need to utilize this higher frequency information.

In our more recent acquisition and analyses of noise segments from the IDC database, we have found that the broadband noise level is sometimes not so high at ARCESS. This seems to agree with observations by Kvaerna (1992) which indicated strong fluctuations in the noise levels and detection threshold at ARCESS by more than one-half magnitude unit during a single month, while the noise levels at the other regional arrays remained more stable. Figure 4 shows the same narrow bandpass filter analysis applied to the simulated ARCESS record for the 1-kt fully decoupled nuclear explosion at NZ with low noise conditions (viz. noise from 04/30/95). In this case the broadband noise on 04/30/95 is about a factor of three to four lower. We see from the broadband (unfiltered) trace at the top that regional P_n and S_n signals are quite apparent on the unprocessed record. The signal-to-noise ratio is roughly a factor of 2.0 for P_n and just above 1.0 for S_n. However, when we look at the individual filter passbands, it is apparent that even at low noise levels some frequency bands will not be useful for detection, location, and identification of small events. In particular, there is still little evidence of the regional signals from the scaled nuclear explosion at frequencies below about 3 Hz; while above 3 Hz signal-to-noise levels are quite high. In fact, maximum amplitudes for the bandpass filter analysis shown in Figure 4 are achieved in the frequency passband from 6 to 12 Hz. The implications again are that regional event characterization methods which make use of high-frequency information in regional seismic signals are likely to be most useful for identifying small or decoupled nuclear explosions at the levels which are currently considered to be of interest for CTBT monitoring.

A test of the relevance of these scaled nuclear explosion data to seismic monitoring like that in the IDC was provided by the 12/31/92 event near NZ (cf. Ryall, 1993). This event of unknown source type had a magnitude of about 2.5 m_b. Therefore, the source size and propagation path for this event should provide a close match to those of our simulated 1-kt fully decoupled NZ explosion. We performed the same bandpass filter analysis shown in Figures 3 and 4 to the ARCESS record for the 12/31/92 event. The results of this comparison were described in detail in the report by Bennett et al. (1994). We observed that above about 3 Hz the simulated decoupled nuclear explosion source produced significantly stronger P signals relative to S (in this case S_n) than the unknown event. The differences become most dramatic in the high frequency passbands (e.g. 6-12 Hz, 8-16 Hz, and 12-20 Hz) where S/P ratios are approximately 1.0 for the unknown event but only about 0.5 for the scaled nuclear explosion records. This behavior for the 12/31/92 event is consistent with that seen for earthquakes and other non-explosion sources in other parts of the world and appears to support the conclusion that the 12/31/92 event was not an explosion.

Another interesting test of seismic monitoring capability with regional stations was provided by the 01/05/95 event in the Ural mountains of Russia. The epicenter of this event reported by the IDC was 59.52 N 56.31 E, and the corresponding magnitude was 4.35 m_b from IDC and 4.7 m_b from PDE. Although this event was located somewhat beyond the normal regional distance range from the Fennoscandian seismic arrays, regional S and L_g phases are apparent on the records at FINESS ($R \approx$ 1660 km), ARCESS ($R \approx 1820$ km), and NORESS ($R \approx 2450$ km); and good regional phase signals were observed at closer stations in Russia. Our investigation of this event has focussed on the seismic signals observed at the nearer Russian stations ARU ($R \approx 360$ km) and OBN ($R \approx 1280$ km). At station ARU we performed a narrow bandpass filter analysis on the vertical-component record, as shown in Figure 5. The filtered traces show a strong R_g phase in the 0.5-2.0 Hz passband. Below about 3 Hz the L_g/P ratios are observed to be large (much greater than 1.0), but above 3 Hz the S/P ratios are about 1.0. For comparison we performed the same bandpass filter analyses on the records from three western European events of different source types recorded at station GRFO (located at about the same epicentral distance). The three events include a Polish rockburst, a Netherlands earthquake, and a Swiss munitions blast and were described in the review report for last years PL Seismic Research Symposium. Across the different frequency bands, the filtered traces appear most similar for the Urals event and the Polish rockburst. L_g/P or S/P ratios were seen to be greater than 1.0 for the Polish rockburst at lower frequencies (below about 3 Hz) and about 1.0 at higher frequencies; as we also saw in the Urals event. Although the earthquake also had large L_g/P or S/P at most frequencies, the energy there in the regional seismic phases appeared more dispersed across the different phase windows. The munitions blast produced relatively smaller L_g/P particularly at frequencies near 1 Hz where the blast signals showed a strong P_g. In the longer period bands a single-station M_S of 3.38 was measured for the Urals event at station OBN. Based on these observations at the Russian stations ARU and OBN, we concluded that the 01/05/95 Urals event was clearly shallow considering the strong R_g phase; this might not be consistent with an earthquake source which would likely be deeper. The relatively weak M_S is also more typically seen in explosions and rockbursts, as are the simple P phases. The most diagnostic feature in these comparisons appears to be that the L_g/P and S/P ratios observed at ARU and OBN are large, 1.0 or above in all frequency bands, which is consistent with behavior seen in other parts of the world for rockburst and eathquakes but does not agree with explosion observations. Based on these observations we concluded that the 01/05/95 Urals event was most likely a rockburst, which appears to be supported by damage reports from a Russian mine in the vicinity of the epicenter.

Conclusions and Recommendations

Regional seismic monitoring is likely to be important to detecting, locating, and identifying small events which are of interest under a CTBT. Theoretical source scaling procedures appear to provide a useful tool for helping to understand the issues associated with characterization of small or decoupled nuclear explosions based on regional seismic measurements. The implications from these studies are that the regional methods which are most likely to be effective for detection, location, and identification of small seismic events will be those which utilize the high-frequency information in the regional signals. We are currently pursuing some additional applications of similar theoretical source scaling analyses for nuclear explosions in other tectonic environments. With regard to application of regional characterization techniques to specific events, which are likely to be encountered in IDC monitoring, we have investigated events near NZ and in the Urals. Based on these and similar studies, we have found that some traditional discriminant measures (e.g. M_S vs m_b, depth-based discriminants) may not be reliable for certain classes of events (e.g. rockbursts). We believe that L_g/P and/or regional S/P ratios frequently provide a diagnostic tool for event identification. Such ratios appear to be most robust when they are compared for multiple passbands covering a fairly broad range of

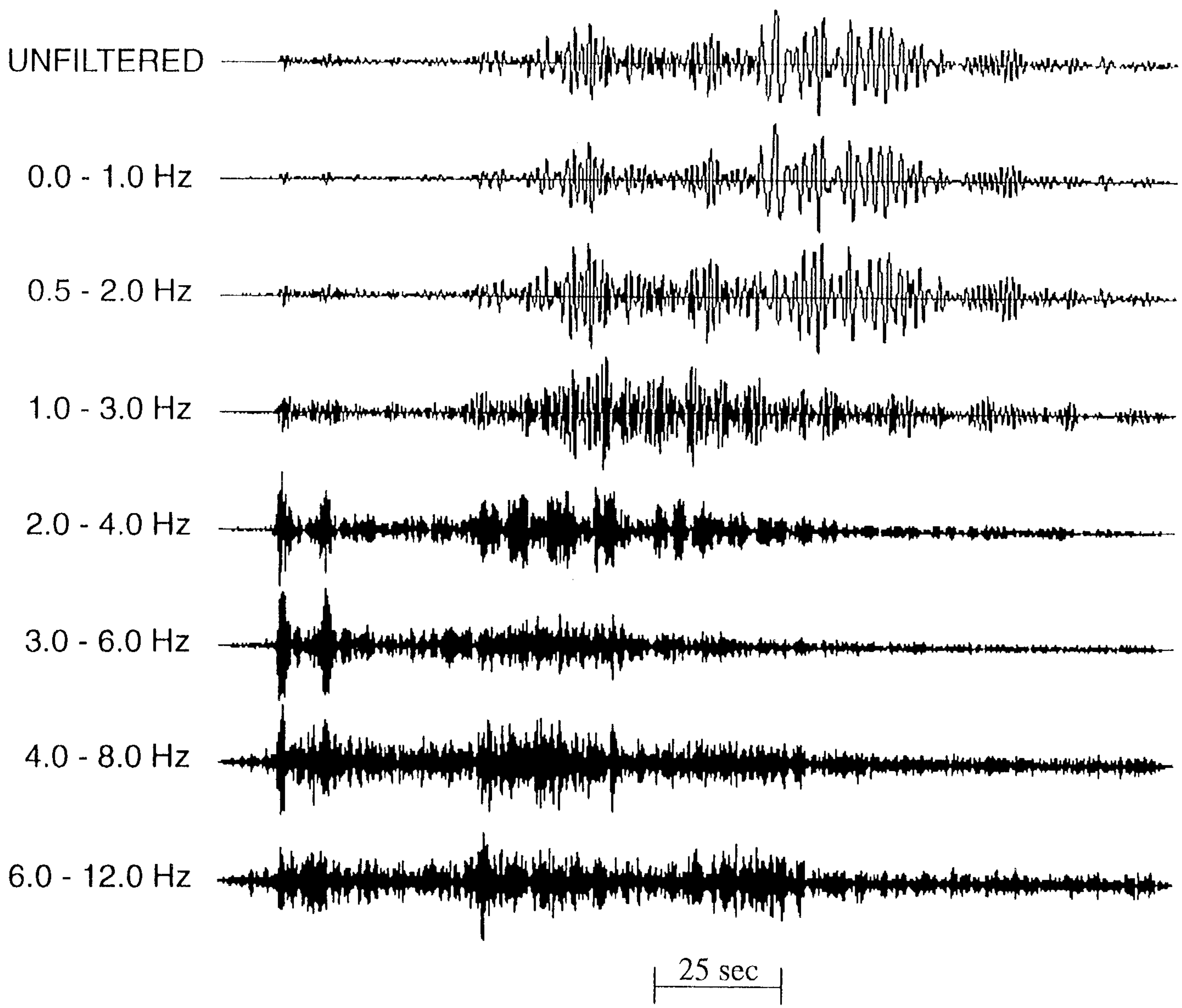

Figure 5. Bandpass filter analysis of the ARU record for the Urals event of January 5, 1995.

frequencies. Systematic studies will be needed to confirm transportability of these kinds of regional discriminants into uncalibrated areas.

References

Bennett, T. J., B. W. Barker, and J. R. Murphy (1994). "Investigation of Regional Seismic Discrimination Issues for Small or Decoupled Nuclear Explosions," PL-TR-94-2260. ADA292744

Kvaerna, T. (1992). "Continuous Seismic Threshold Monitoring of the Northern Novaya Zemlya Test Site: Long-Term Operational Characteristics," PL-TR-92-2118, ADA252890.

Mueller, R. A., and J. R. Murphy (1971). "Seismic Characteristics of Underground Nuclear Detonations. Part I. Seismic Spectrum Scaling," Bull. Seism. Soc. Am. 61, pp. 1675 - 1692.

Ryall, A. S. (1993). The Novaya Zemlya Event of 31 December 1992 and Seismic Identification Issues, Executive Summary, Published in Conjunction with the 15th Annual Seismic Research Symposium, 8 - 10 September 1993, Vail, Colorado. PL-TR-93-2160, ADA271458