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Detection and Identification of Small Regional Seismic Events

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Only very limited experience exists for regional seismic signals from small or decoupled nuclear explosions, which would be important in a CTBT monitoring environment. The goal of this research has been to enhance the experience base for such events at the prototype International Data Center (IDC) and to identify potential techniques and limitations of IDC seismic monitoring at the low magnitude levels appropriate to a CTBT. To accomplish this objective theoretical source scaling was used to scale the original records observed from underground nuclear explosions 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. We then analyzed the simulated records in the time and frequency domains to assess their implications for detection, location, and identification. The regional signal characteristics for the scaled explosions can then be compared to similar behavior in signals from small events of other source types. In a separate study under this contract, we also investigated regional seismic identification techniques for some specific events recently detected by the IDC.

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Table of Contents

List of Illustrations

List of Tables

Page

1. Introduction

Implementation of a Comprehensive Test Ban Treaty (CTBT) governing nuclear weapons tests would impose stringent requirements on seismic monitoring technology which exceed traditional capabilities. Two factors which contribute significantly to the dichotomy between these new requirements and historical monitoring experience are (1) the need under a CTBT to discern events which are much smaller than those previously considered relevant, and (2) extension of capabilities to countries and tectonic regions which were of little concern for bilateral or trilateral agreements with high testing thresholds. Seismic monitoring, such as that conducted under the GSETT series, has demonstrated the value of regional networks for helping to locate and identify small seismic events in many different regions of the world. Systematic regional monitoring extended on a global scale is likely to produce large quantities of seismic events which would require characterization under a CTBT. This observation appears to be corroborated by preliminary experience with the prototype of the International Data Center (IDC) operating at the ARPA Center for Monitoring Research (CMR). Seismic discrimination based on measurements from stations in the regional distance range is likely to play a key role in identification of most events being reported by the IDC. The research reported here was designed to assess and help improve regional seismic identification techniques for the IDC.

The capability for regional seismic monitoring in several areas of Eurasia has improved significantly in recent years with the advent of the high-quality ARPA regional arrays at NORESS, ARCESS, GERESS, and FINESA. These arrays are now routinely providing excellent regional seismic data for events in Scandinavia and northern Europe, and additional development of regional arrays and high-quality single stations in other parts of Eurasia is enhancing regional monitoring in those areas. However, one problem with the IDC database is that it includes very little experience with underground nuclear explosion tests and no practical experience with small nuclear explosions at the level which would be of interest under a CTBT. One goal of this research program has been to attempt to simulate regional signals which would be produced by such small nuclear explosion tests (e.g. 1 kt fully decoupled). To achieve this objective we have applied Mueller-Murphy source scaling theory to scale seismic signals from larger explosions down to levels representative of the smaller events. The down-scaled records have been compared to and embedded in representative ambient seismic noise to assess capabilities with respect to regional signal detection and frequency bands which may be useful for discrimination.

The source scaling procedures were first applied to the signals recorded at NORESS, ARCESS, and FINESA regional arrays from three nuclear explosions including two NZ events and one PNE north of Arkhangel'sk, Russia. We subsequently have applied similar source scaling to the regional signals from explosions in two other regions: the Soviet JVE nuclear explosion in East Kazakhstan and a Chinese nuclear test at Lop Nor in northwestern China. For the former we used records from two high-quality digital stations: the Incorporated Research Institutions for Seismology (IRIS) station at Garm and the Chinese Digital Seismic Network (CDSN) station at Urumchi. The Lop Nor nuclear test was also recorded at the regional station at Garm. The records were scaled down to 1-kt fully decoupled, as well as intermediate yields, producing a reduction in amplitude and frequency shift toward higher frequencies in moving toward lower yields. The scaled signals were superimposed on a variety of noise samples from the same stations including several long signal-free waveform segments. Our preliminary findings are that the signals were usually difficult to discern on the broadband records. The useful far-regional signals from small or decoupled nuclear explosions may be constrained to very limited high-frequency bands. This may limit the capabilities of some regional detection and identification techniques. The scaling theory also seems to predict that the regional S/P or L_g/P ratio discriminant might perform better for small events, but there are some caveats. A digital tape containing the results of the initial scaling studies using the Scandinavian ARPA regional arrays for two different noise segments has been supplied to the ARPA Center for Seismic Studies for further processing and testing of the IMS/NMRD system.

In addition to these scaling exercises, we have investigated regional identification characteristics for selected events reported by the IDC. Events analyzed for this part of the study included a seismic event in the central Ural mountains of Russia on 01/05/95 and an event at Novaya Zemlya (NZ) on 12/31/92. Regional seismic signals from these events were analyzed and compared with similar measurements from different source types in an attempt to categorize these unknown sources. We concluded that the Urals event was most likely a rockburst or mining-induced tremor based on a strong R_g phase (indicative of shallow focal depth), weak M_S relative to m_b (typically seen in explosions and rockbursts), and relatively large L_g/P or S/P over a fairly broad frequency band (usually seen in earthquakes or rockbursts but not explosions). Analyses of the NZ event indicated that it was probably an earthquake or mining-induced tremor, again because of the relatively large S/P at the regional array stations which is not normally seen in underground nuclear explosions from NZ.

This report consists of five sections including this Introduction. Section 2 reviews the source scaling procedures and describes the data which were used in these scaling exercises. Section 3 describes details of the application of the scaling procedures to specific data and the results of analyses performed on the scaled time histories. Section 4 includes the description of the investigations and discrimination analyses which were performed on the NZ event and the central Urals event. Finally, Section 5 provides a summary of our results and main conclusions.

2. Source Scaling and Data Description

Historically teleseismic signal measurements of underground nuclear explosion tests have been relied on to detect, locate, and discriminate them from other source types. Such teleseismic techniques generally work well down to magnitude levels near 3.5 to 4.0 m_b for events in the vicinity of known test sites. However, teleseismic techniques would not be adequate as the magnitudes of interest are pushed to lower thresholds and as we begin to look at other source regions in the context of a CTBT. For smaller events detection, location, and discrimination techniques should utilize observations at regional stations. This need for reliance on regional station measurements for identification of small events has been recognized for more than a decade and led to the development of high-quality regional seismic array stations such as those in Scandinavia and Europe. However, several factors have prevented investigators from taking full advantage of the capabilities of regional seismic arrays for event identification. One significant factor impeding the development of reliable regional identification techniques has been the limitations on the availability of small nuclear explosion tests in various tectonic regions which can be used to test and calibrate regional monitoring methods. A principal goal of this current research has been to investigate the use of explosion source scaling procedures to simulate regional signals from small nuclear explosion sources. It is envisioned that these simulated signals can be used to test the capabilities of seismic monitoring systems, such as the IDC, for detecting, locating, and identifying small nuclear explosion tests down at the small magnitude levels which would be relevant under a CTBT.

In our first report (Bennett et al, 1994a) we described the Mueller-Murphy explosion source scaling procedures used in this study and applied those techniques to signals recorded at Scandinavian regional array stations. In this section of this report, we will briefly review those procedures and outline their application to additional data from explosions in other source regions.

2.1 Explosion Source Scaling Relations

According to source scaling theory, if we assume the propagation path transfer function is common to two explosions, we can then express the ground motion spectrum for one event in terms of the spectrum for the other as

$$Z_2(\omega) = \frac{S_2(\omega)}{S_1(\omega)} Z_1(\omega) \qquad (1)$$

where S_1 and S_2 are seismic source spectra for the two explosions. So, if we can estimate the seismic source functions for two explosions, we can predict the ground motion spectrum for the second explosion based on an observed spectrum for the first explosion.

The seismic source function for underground nuclear explosions accounts for the coupling of energy released by the explosion into the seismic wave field radiated outward from the source. Rodean (1981) and Bache (1982) reviewed much of the early work aimed at developing quantitative understanding of seismic coupling and the seismic source function for explosion sources. The ground motion is usually developed in terms of a reduced displacement potential which depends on the material properties of the source region, depth, and explosion yield. Theoretical models based on constitutive behavior of the near source geologic materials can be used to determine the potential function. However, in this discussion we follow the development of Mueller and Murphy (1971) or von Seggern and Blandford (1972) which present the reduced displacement potential as an analytic function which is constrained by empirical observations from prior underground nuclear explosions.

For a simple, spherically symmetric model of the explosion source, the source spectral ratio for two explosions (cf. Mueller and Murphy, 1971) can be written as:

$$\frac{S_2(\omega)}{S_1(\omega)} = \frac{p_2(\omega)}{p_1(\omega)} \frac{r_{el_2}}{r_{el_1}} \frac{\omega_{01}^2 + i\omega_{01}\omega - \beta\omega^2}{\omega_{02}^2 + i\omega_{02}\omega - \beta\omega^2} \qquad (2)$$

where $p(\omega)$ is the Fourier transform of the spherically symmetric pressure from the explosion acting at the elastic radius, r_{el}, and

$$\omega_0 = \frac{\alpha}{r_{el}}$$

$$\beta = \frac{\lambda + 2\mu}{4\mu}$$

where α is the compressional wave velocity and λ and μ are the Lamé constants characteristic of the source medium. For explosions at the same depth in a fixed medium, the elastic transition pressure should be constant; then, assuming a step-function approximation for the pressure profiles acting at the elastic radii, it follows that $p_2(\omega) = p_1(\omega)$ and that the modulus of the source spectral ratio can be written simply as

$$|S(\omega)| = \frac{|S_2(\omega)|}{|S_1(\omega)|} = \frac{r_{el_2}}{r_{el_1}} \sqrt{\frac{\left(\omega_{01}^2 - \beta\omega^2\right)^2 + \omega_{01}^2\omega^2}{\left(\omega_{02}^2 - \beta\omega^2\right)^2 + \omega_{02}^2\omega^2}} \qquad (3)$$

From this it can be seen after some simplification that the high- and low-frequency asymptotic values of the source spectral ratio are just proportional to the ratio of the elastic radii and the cube of the elastic radii respectively. Or, since r_{el} is proportional to the cube root of the yield, for explosions at the same depth of burial in a given source medium, at low frequencies the ratio of the source spectra of the two explosions is just equal to the ratio of their yields; while at the high-frequency limit the ratio of the source spectra is equal to the cube root of the yield ratio. Analogous expressions for the seismograms from different explosion sources in the same source region can be written for the time domain.

In the following we have used these scaling relationships to scale down the regional signals from several large-yield underground nuclear explosions to obtain signals representative of smaller yield events, including yields approaching 1 kt fully decoupled, which would be appropriate to the low-threshold monitoring problem. The scaling relations described above are presented in terms of the elastic radius, the distance from the center of the explosion source beyond which the medium response to the induced motion is approximately linear. The elastic radii for underground nuclear explosions are rarely observed directly but are determined instead indirectly from empirical measurements (e.g. free-field ground motions) and assuming modified cube-root scaling with yield. Thus, for a particular source medium an elastic radius corresponding to a particular yield and source depth can be estimated from the appropriate empirical relationships. Murphy (1977) showed that near-regional and regional broad-band seismic data and teleseismic body-wave magnitudes are generally consistent with this modified source model for United States explosions in various materials.

In our analyses we have been interested in assessing the influence of the explosion yield difference on the detectability and identification capability for small nuclear explosions. For this purpose we have assumed a fixed depth so that the elastic radius takes on a simplified cube-root dependence on yield

$$r_{el} = D' Y^{\frac{1}{3}} \tag{4}$$

where, for example, $D' = 186 \ m/kt^{\frac{1}{3}}$ for explosions in a saturated tuff/rhyolite medium at 150 m source depth.

The above relationship combined with the source scaling theory would be sufficient to perform the desired scaling for explosions of known yield. However, except for some recently published yields of nuclear explosions from the former Soviet Union (cf. Vergino; 1989a,b), we only know the yields for United States nuclear tests. A number of recent studies (e.g. Ringdal et al., 1992) indicate that reasonably accurate estimates of the yields of nuclear explosions at several test areas in the former Soviet Union can be obtained from magnitude-yield relationships. The magnitude most often used in explosion yield estimation is the teleseismic body-wave magnitude, m_b. The relationship between m_b and yield for application at the Balapan test site has been determined to be

$$m_b = 4.45 + 0.75 \log Y \tag{5}$$

The recently released yields for nuclear explosions in the former Soviet Union confirm that this magnitude-yield relationship probably provides reasonable estimates of the yields for most historic events. For purposes of this study we assume that this magnitude-yield relationship can be extrapolated to lower magnitude explosions in order to estimate the corresponding yields and is also applicable to Russian tests in other areas (viz. Novaya Zemlya and north of Arkhangel'sk) as well as for the Chinese test site at Lop Nor.

A final element to be considered in our processing scheme is decoupling. Although theoretical studies originally predicted that large decoupling factors (> 200) could be achieved for underground nuclear explosions detonated in a cavity, subsequent observations have suggested that the maximum achievable decoupling is somewhat lower. The current belief is that a decoupling factor of about 70 can be attained at low frequencies (OTA, 1988). A decoupling factor of 70 implies that the low-frequency spectral level for seismic signals from a fully-decoupled explosion would be only about $\frac{1}{70}$ that of a fully-coupled (tamped) explosion of the same yield.

We can handle the influence of this decoupling factor at different frequencies in terms of the explosion source scaling theory presented above. In particular, the scaling relations indicate that the low-frequency spectral ratio behaves as the ratio of the yields while the high-frequency spectral ratio behaves as the cube-root of the ratio of the yields. This implies that the decoupling factor for cavity decoupling of underground explosions is greatly reduced at high frequencies. In particular, if the decoupling factor at low frequencies is taken to be 70, the decoupling factor at high frequencies would be expected to be only about $\sqrt[3]{70}$, or about four to five. At intermediate frequencies the decoupling factor goes through a transition from high to low; the corner frequencies at which the transition occurs are predictable from the scaling theory and are proportional to the ratio of the medium velocity to the elastic radii of the two explosions.

Figure 1, taken from Bennett et al. (1994a), shows the scaling factor relating a 1 kt tamped explosion in granite to a 1 kt fully-decoupled explosion in the same medium. The decoupling factor is about 70 at low frequencies up to about 2 - 3 Hz and drops off to the predicted factor of between 5 and 6 near the 20 Hz upper limit of the plot. Over the intervening frequency range a rapid decrease in the decoupling factor is predicted. Thus, the scaling theory predicts that the seismic signals from the decoupled explosion should be reduced at all frequencies but also that high frequencies should be reduced much less, or enhanced, relative to low frequencies in the seismograms for the decoupled events.

In the analyses described below in Section 3 of this report, we have used the scaling theory just described to assess how smaller underground nuclear explosion tests might behave in the detection, location, and identification environment pertinent to a CTBT.

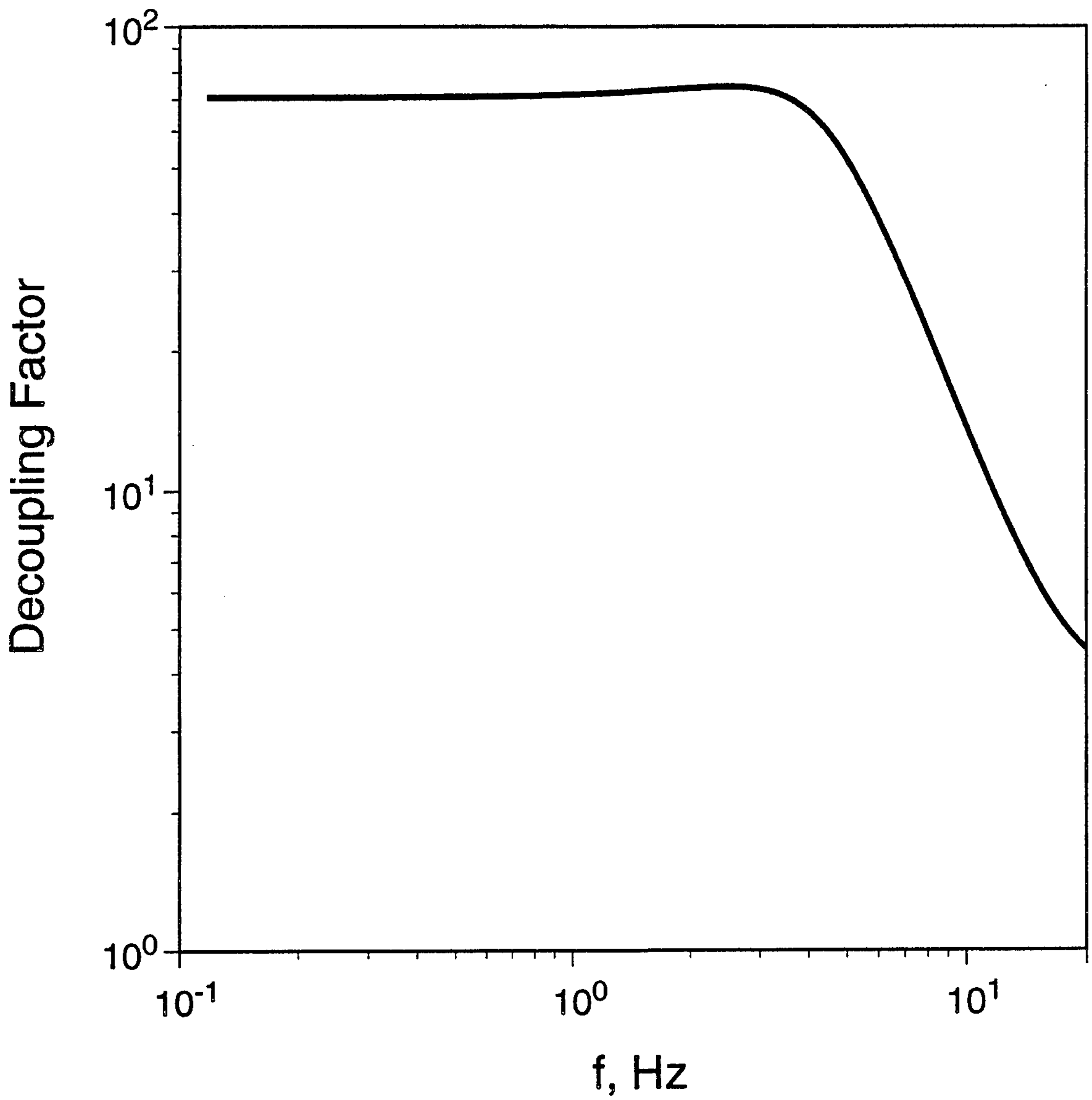

Figure 1. Predicted decoupling factor as a function of frequency based on source scaling theory relating a 1kt tamped nuclear explosion to a 1kt fully-decoupled nuclear explosion.

2.2 Data Used in Scaling Studies

A significant increase in regional seismic monitoring capability began in the late 1980's and early 1990's. This enhanced capability is largely due to the installation of the high-quality ARPA regional arrays in Scandinavia and northern Europe and the subsequent improvement of digital regional stations and arrays in other areas of the world. These improvements have included installation and upgrades to the Incorporated Research Institutions for Seismology (IRIS) stations and Chinese Digital Seismic Network (CDSN) stations in Eurasia. However, this improved regional monitoring capability has been accompanied by a decline in nuclear explosion testing. Furthermore, the ARPA regional arrays in Scandinavia and northern Europe are located beyond the regional distance range for several of the nuclear explosion testing areas which have been most active in the recent past (e.g. NTS, Balapan, Lop Nor, French Pacific). As a result, there is only a very limited sample of regional records from underground nuclear explosions recorded by these modern high-quality stations which can be used to investigate and test monitoring capability and limitations on the relevant data. Furthermore, the nuclear explosions have generally been large and cannot, therefore, be used directly to provide a test of capabilities at the lower thresholds of interest for a CTBT.

For our analyses we have collected regional records from seven underground nuclear explosions (cf. Table 1). The locations of the events and stations are shown in Figure 2. Four of the explosions were at Novaya Zemlya (NZ) and were recorded by the ARPA regional arrays in Scandinavia. The PNE north of Arkhangel'sk and east of the White Sea occurred on 07/18/85, and the only regional array which was operational and recorded this event was NORESS. The epicentral distances are approximately 2260 km to NORESS, 1100 km to ARCESS, and 1770 km to FINESA for the NZ events. The epicentral distance to NORESS for the PNE is 1560 km. So, in general, these explosions were in the mid- to far-regional distance range from the Scandinavian ARPA regional arrays. Only the 10/24/90 NZ explosion was recorded by all three Scandinavian regional arrays, and this event has been the focus for most of our analyses.

In addition to the events just described, we also collected and analyzed regional records from the Soviet Joint Verification Experiment (JVE) nuclear explosion on 09/14/88 at the Balapan Test Site near Semipalatinsk in East Kazakhstan and from a nuclear test on 08/16/90 at the Chinese Test Site at Lop

Table 1

Explosion Database

Date	Origin Time	Lat(°N)	Lon(°E)	mb	Stations
08/02/87	02:00:00	73.34	54.63	5.8	NORESS
05/07/88	22:49:58	73.36	54.45	5.6	NORESS, ARCESS
12/04/88	05:19:53	73.39	55.00	5.7	NORESS, ARCESS
10/24/90	14:57:58	73.36	54.71	5.7	NORESS, ARCESS, FINESA
07/18/85	21:14:57	65.97	40.86	5.0	NORESS
09/14/88	03:59:57	49.83	78.81	6.0	WMQ, GAR
08/16/90	04:59:58	41.56	88.77	6.2	GAR

Noise Samples

Date	Time	Duration (sec)	Stations
04/23/92	05:15:00	1500	NORESS, ARCESS, FINESA
06/28/92	12:30:00	1500	NORESS, ARCESS
06/28/92	15:37:00	1500	NORESS, FINESA
04/30/95	08:00:01	14000	ARCESS
09/14/88	04:51:45	550	WMQ
09/14/88	03:53:00	550	GAR
08/16/90	04:00:00	1800	GAR

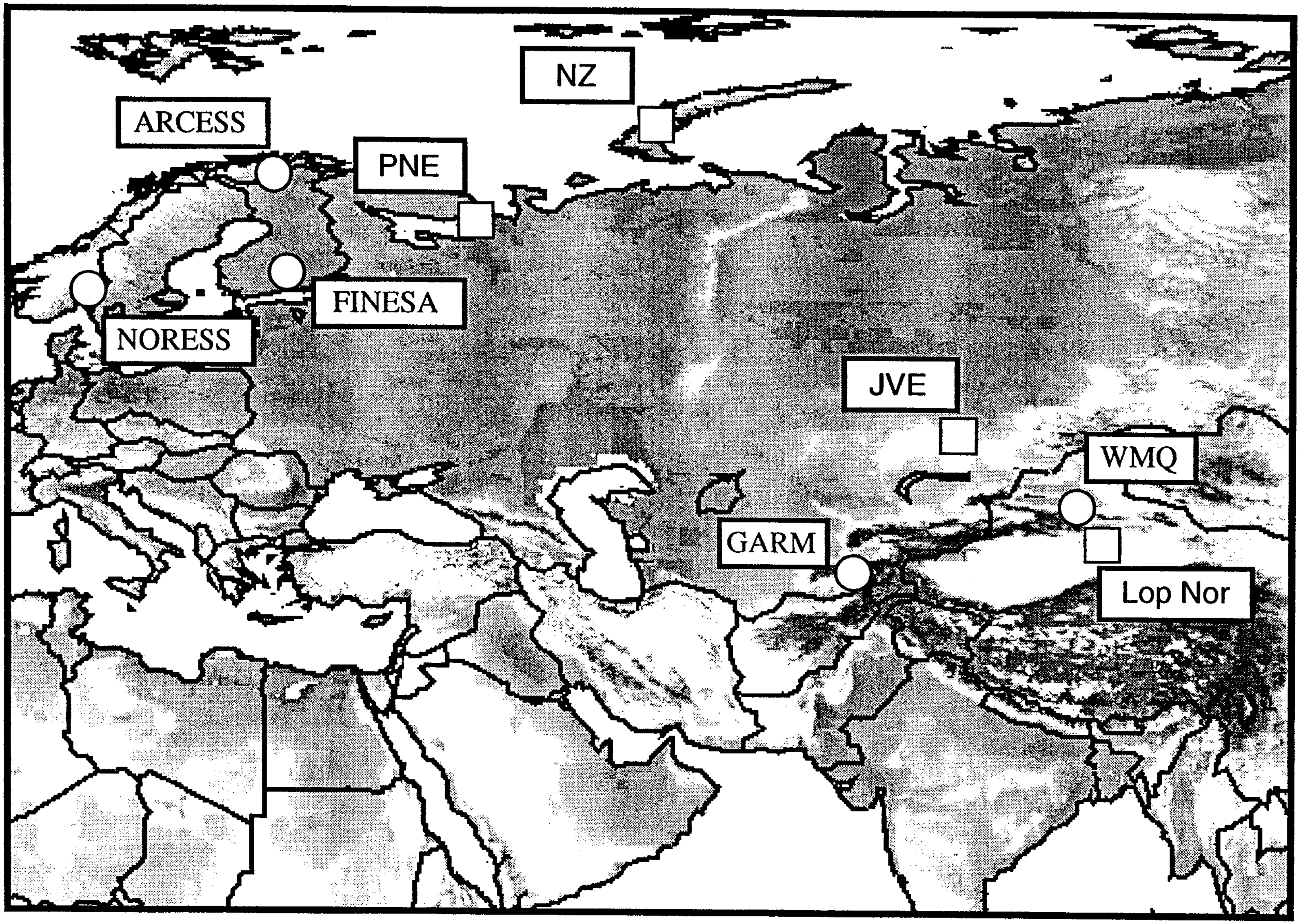

Figure 2. Locations of stations (◯) and events (□) used in the source scaling studies of regional signals from small nuclear explosions.

Nor (cf. Figure 2). In our analyses we used records from the JVE explosion recorded at the IRIS station GAR at about 1380 km and at the CDSN station WMQ at about 950 km. For the 08/16/90 Lop Nor nuclear explosion we used the record at station GAR at about 1590 km.

The waveforms used in our analyses were retrieved from the IMS database at the Center for Monitoring Research (CMR) and from IRIS. For each event we obtained the entire waveform segments which were available around the predicted signal arrival times at each station. For most events recorded by the regional arrays, we retrieved all array elements. The data quality was generally good except for a few spikes and data dropouts on some channels.

As we described above, our procedure involves adding the scaled time histories back into noise segments representative of the normal background noise at the station. For use as these background noise segments, we attempted to retrieve data at times when there were no signals (cf. Bennett et al., 1994a). However, some difficulty was encountered in finding long noise segments from the IMS database at CMR because most of the data which were available at that time represented detected signals. Nevertheless, three relatively long record segments with no apparent signals were retrieved for the Scandinavian ARPA array stations. These segments correspond to the noise samples from 1992 indicated at the bottom of Table 1. In our prior report we described how those segments were used to simulate a longer data stream including an embedded 1 kt fully decoupled nuclear explosion which could be used to test the CMR monitoring system. The digital data tape corresponding to this data stream was provided to the CMR at that time.

In our current studies we have been less concerned about the detailed simulation of monitoring scenarios and have focused instead on analyzing the characteristics of small nuclear explosions in other source areas and with other background noise conditions. For use in the investigation of alternative noise conditions, we retrieved an additional very-long noise segment from the ARCESS array for 04/30/95, as shown in Table 1. It should be noted that the IDC database at CMR now includes nearly continuous data for recent dates, so that longer signal-free waveform segments are available. Noise segments recorded at the IRIS station GAR near the times of the Soviet JVE and of the 08/16/90 Lop Nor nuclear tests were also retrieved in addition to a noise segment at the CDSN station WMQ from near the time of the Soviet JVE.

3. Simulation of Regional Signals for Small Nuclear Explosions Using Scaling Theory

The explosion source scaling theory has been applied to the database described in Section 2 of this report. Our objective was to scale down the signals from the large nuclear explosions to the lower thresholds (e.g. 1 kt decoupled) which are being discussed in conjunction with more comprehensive test ban treaties. During the initial phases of this research we worked mainly with three events: the 12/04/88 and 10/24/90 NZ explosions and the 7/18/85 PNE recorded by the Scandinavian regional arrays. We assessed the detectability of the scaled regional signals from those events in relation to the available noise segments and generated complete array data segments for the scaled signals embedded in extended versions of the noise samples. A copy of the simulated time histories was provided to CMR to be used in testing the IMS system and regional discrimination capabilities for low-yield and decoupled nuclear explosion tests. Over the past year this research program has focused more on applying the scaling procedures to nuclear explosions in other areas and under alternate noise conditions.

3.1 Application of Scaling Procedures to Simulate Small Underground Nuclear Explosions at Regional Stations

To illustrate the steps in the simulation procedure, we briefly review here the application of the scaling to the 10/24/90 NZ explosion, as described previously by Bennett et al. (1994a). The 10/24/90 NZ explosion had a magnitude of 5.7 m_b. The scaling is performed using the elastic radius relationships described. Assuming the explosion was fully tamped, the 5.7 m_b corresponds to a yield of about 50 kt and an elastic radius of about 685 m. An explosion of 1 kt fully decoupled has an equivalent elastic radius of 45 m and would be expected to produce a magnitude of about 2.6 m_b.

Figure 3 illustrates the application of the scaling process to the 10/24/90 NZ explosion. In the original broadband records at the top of the figure, we see the large amplitude regional signals with sharp P onsets at all three array stations. The P signal shows some complexity with the coda gradually decreasing before the arrival of complex regional S and L_g phases. The regional S/L_g phase has a relatively clear onset at ARA0 but not at FIA0 or NRA0 where the signal level is relatively low and dispersed in character.

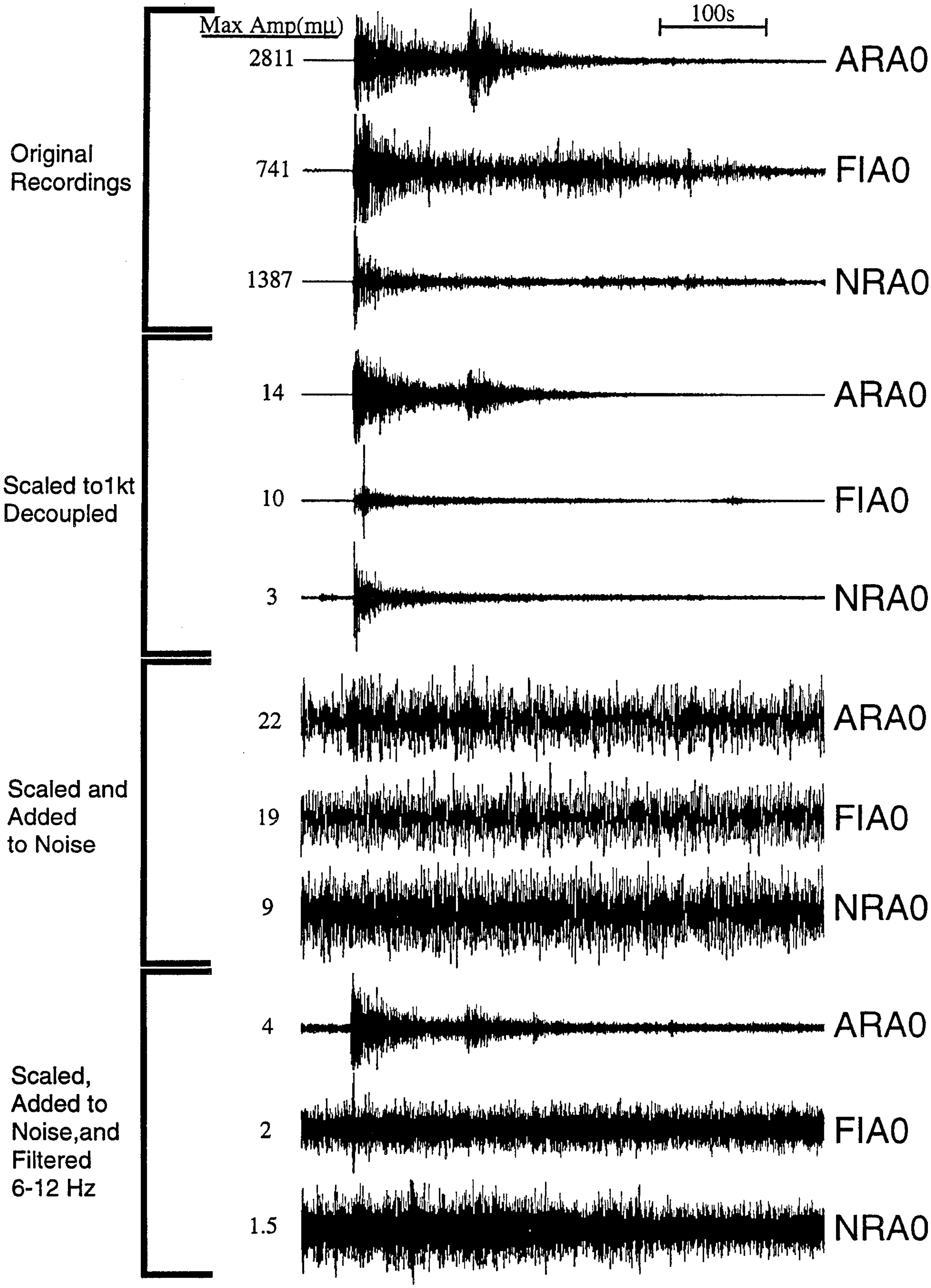

Figure 3. Examples of application of source-scaling process to NZ explosion at ARPA regional arrays.

The next set of three records shows the effect of scaling on the same signals at the three stations. The reduction in the peak amplitude is about a factor of 200 at ARA0 and between 400 and 500 at NRA0. However, at FIA0 the original record seems to have moderate clipping in the P-wave window which shows up as a high-frequency spike in the scaled record. Looking at the signals away from the spike time, maximum amplitudes on the scaled trace are about a factor of three lower, or about 3 mμ. The original (unscaled) FIA0 trace appears to be only moderately clipped, so that the maximum amplitude is probably not much greater than 750 mμ. Thus, the effect of scaling on the signals at FIA0 appears to reduce the maximum amplitude by about a factor of 250. The scaling procedure at all three regional array stations seems to reduce the significance of later regional phases relative to the original P. This might be associated with relatively greater high-frequency content in the regional P compared to other regional phases which is enhanced in the scaling process on the broadband records.

The third set of three records shows the broadband scaled records added into the 04/23/92 noise segments from each of the ARPA regional array stations. In all cases the noise level on the broadband records is greater than the scaled signal records, so that signals are no longer apparent. The results suggest that the broadband records would not be particularly useful for detecting or measuring the strength of regional signals from such small explosions in this far-regional distance range.

Finally, the bottom three records show the effects of application of a bandpass filter to the scaled records superimposed on the noise. We actually performed a bandpass filter analysis using a series of several different filters on the time histories. In general, no signals could be seen in the low-frequency bands (below about 3 Hz) at any of the stations. However, the higher frequency passbands did show signals at some stations. In particular, we see here regional P, S and L_g in the 6 - 12 Hz frequency band at ARA0. The apparent arrival at FIA0 near the expected P time appears to be associated with the clipping problem at FINESA cited above. We conclude from this that high-frequency bands are likely to be the most useful for detecting and analyzing regional phases from small nuclear explosions, and farther regional stations may only be helpful if noise conditions are favorable.

3.2 Additional Results for New Noise Measurements at ARCESS

The importance of site noise conditions in assessing the detection thresholds and identification capability at regional stations was emphasized by Bennett et al. (1994a) in discussing the effects of the high variability in seismic background noise at the ARCESS array. In the associated scaling exercises and as illustrated in Figure 3 above, the simulation of a 1 kt fully decoupled NZ nuclear explosion recorded at ARCESS produced signal levels just about at the background noise, when using the noise segments from 04/23/92. Kvaerna (1992) in his investigation of Continuous Seismic Threshold Monitoring of NZ noted strong fluctuations in the ARCESS noise which frequently impeded detection capability of the ARPA regional arrays for that source area. Bennett et al. (1994a) discussed further the implications of the variability in background noise conditions reported by Kvaerna and other authors and their bearing on regional monitoring. From the studies by Kvaerna, the variations in the threshold at ARCESS are more than 0.5 magnitude units, from about 2.0 m_b during quiet noise conditions to about 2.6 m_b during high noise. It should be noted that the m_b measurements reported here are based on a regional measurement made by NORSAR and may not correlate directly with the more traditional teleseismic m_b scale (cf. Murphy et al., 1995), although we might expect the relative differences to be similar. The high-noise conditions at ARCESS are believed to correlate with high winds and severe weather (cf. Kvaerna, 1992). In comparison, the thresholds at NORESS were seen to be much more stable varying only between about 2.5 and 2.7 m_b over the same time period.

To help improve understanding of the influence of ARCESS noise levels on the detectability of small events near NZ, we retrieved the additional long noise segment from 04/30/95, as noted in Section 2. Figure 4 shows the vertical component record at ARA0 for this nearly 4-hour long segment. In this figure it should be noted that the total noise sample is broken up into eight subsegments which follow after one another and which have been individually scaled for display purposes. The maximum amplitude seen during this 4-hour period on the broadband records is only a little above 10 mμ, which is only about half as great as the maximum broadband noise for the segment from 04/23/92 used in our previous analyses. As noted above, large variations in the background seismic noise at ARCESS are to be expected depending on wind

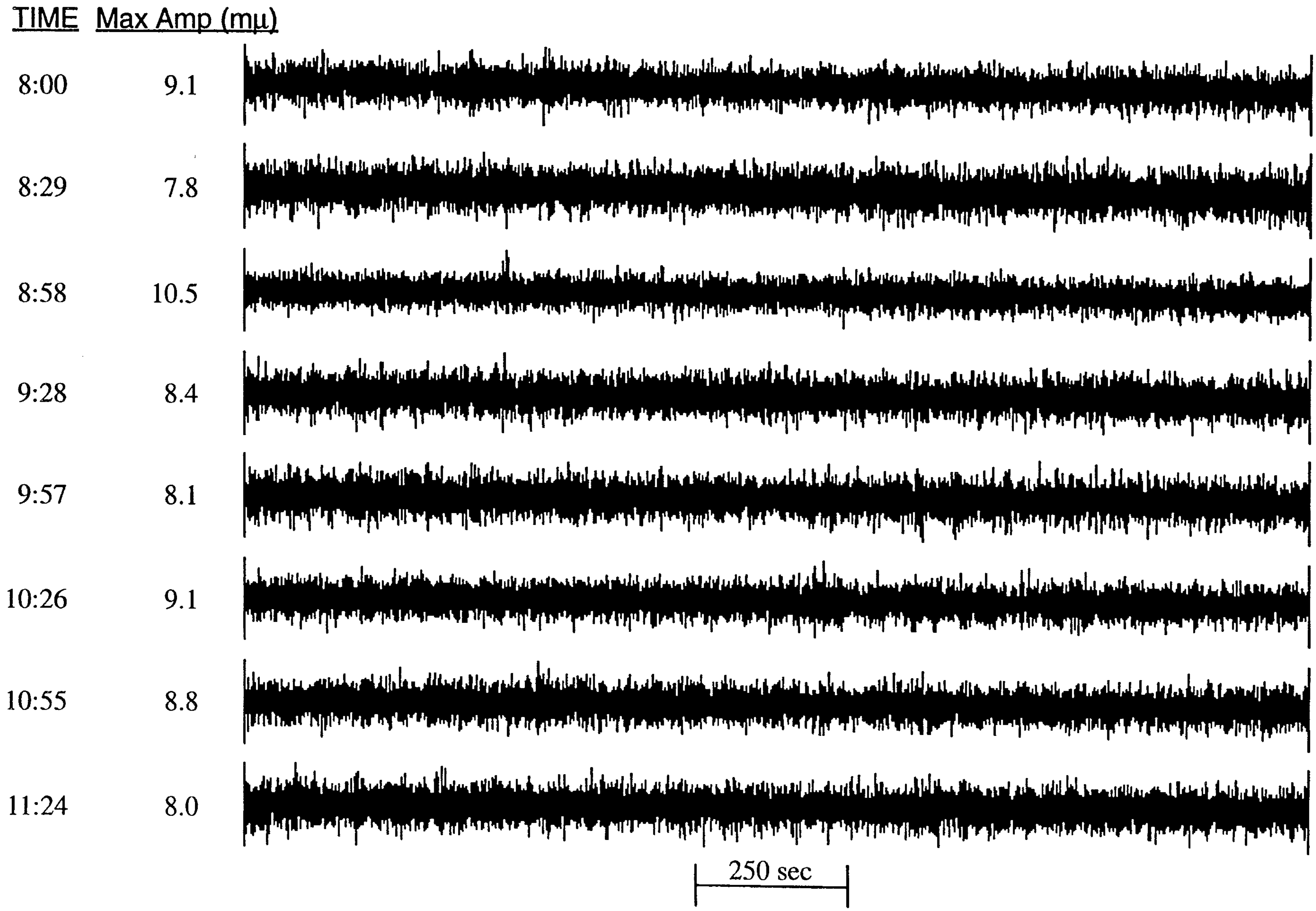

Figure 4. Long (~4 hour) noise segment recorded at ARCESS on 04/30/95.

and other weather conditions. In contrast, the broadband amplitude levels recorded at ARCESS during this 4-hour period on 04/30/95 show only very small variations between about 8 mμ and 10 mμ. We next seek to answer how the lower noise levels at ARCESS affect detection and monitoring capability for small regional events.

Figure 5 shows a comparison of the original broadband (UNFILTERED) records simulating the 1 kt fully decoupled NZ explosion embedded in the two different background noise conditions (viz. 04/23/92 noise at the top and 04/30/95 noise at the bottom). The NZ explosion used in the simulation is the 10/24/90 explosion scaled down to 1 kt fully decoupled. Comparing the top UNFILTERED traces from the two groups of traces, the regional signals are much more apparent on the lower-noise day (04/30/95). The signal-to-noise (S/N) ratio is about two for the P_n phase, somewhat greater than one for S_n, and near one for the L_g on the broadband traces.

The additional traces in Figure 5 correspond to narrow-bandpass filter analyses of the two simulations. We see from these analyses that, even though the signals were more apparent on the broadband records, the regional signals are still concentrated in high-frequency bands. In fact, we see from the bandpass filter results that it's only above about 3 Hz that the signals rise above the background noise; and this holds for the lower as well as the higher background noise conditions. Therefore, lower broadband background seismic noise conditions at ARCESS do not necessarily imply improved detection thresholds nor do they mean that lower frequencies can be used to help discriminate smaller events.

3.3 Application to Events from Other Source Areas

As noted above in Section 2, we have also compiled seismic data from the regional distance range for selected events in other source areas. These events included the JVE underground nuclear explosion test in the southern part of the former Soviet Union and a Chinese nuclear test. The JVE occurred at the Balapan test site in East Kazakhstan, which was long the most active testing area for nuclear weapons in the former Soviet Union but which is now dormant. This event was recorded to the south in Garm by a high-quality digital station (GAR) established by IRIS and to the southeast at station Urumchi (WMQ) which is a high-quality digital station established in northwestern China as part of the CDSN. The Chinese nuclear explosion which we analyzed

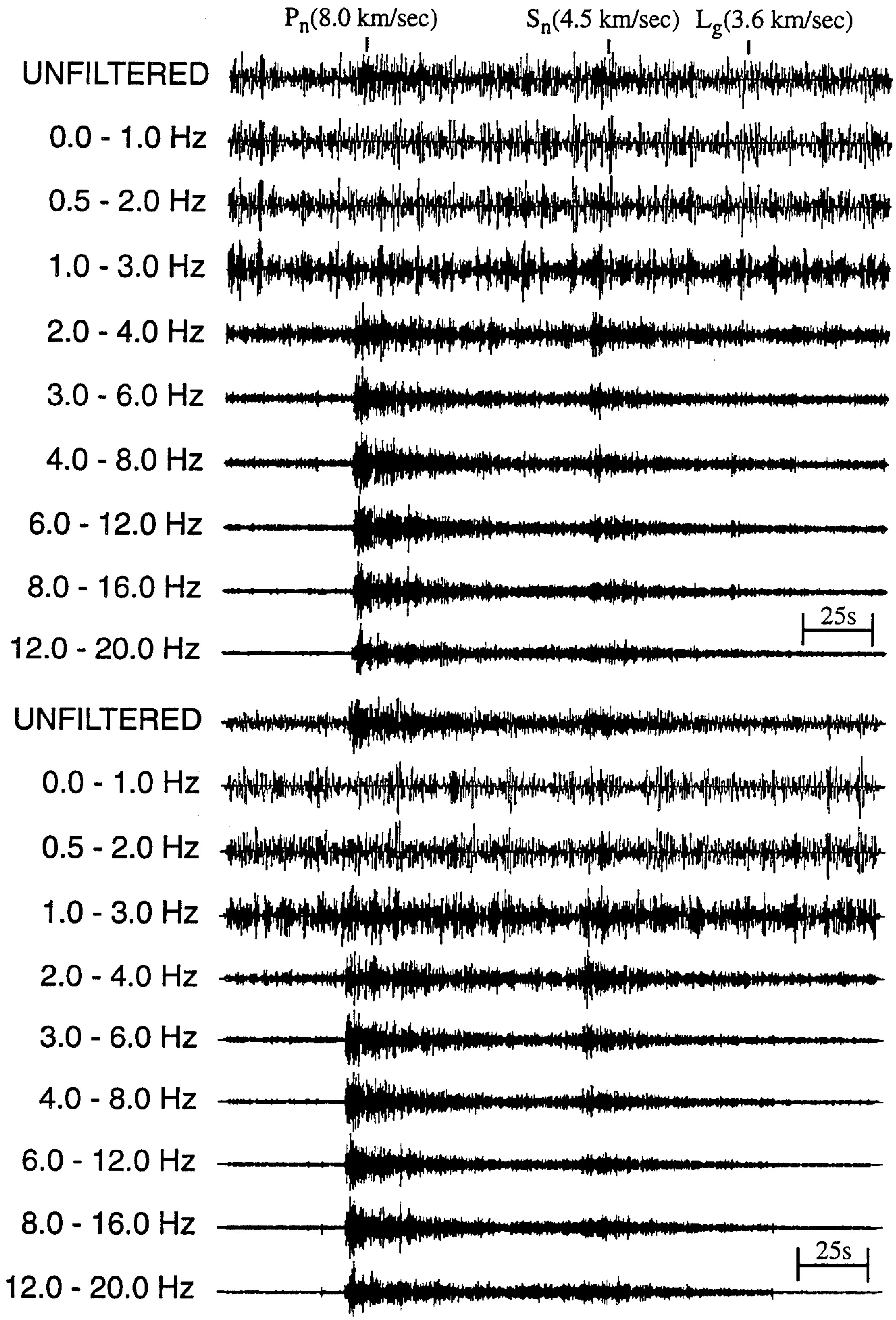

Figure 5. Application of band-pass filter analysis to vertical-component ARA0 recording of the 10/24/90 NZ explosion scaled down to 1kt fully decoupled for the 04/23/92 noise sample (top) and the 04/30/95 noise sample (bottom).

occurred at the Lop Nor test site in northwestern China which was again recorded at the station in Garm. Although the station at Urumchi is also located in the general vicinity of the Lop Nor test site, it was not operational at the time of the latter explosion test. For the analyses which follow, we have utilized the vertical-component, broadband records.

In applying our simulation procedures to explosions in these other source areas, we have followed a somewhat different approach. We have used the scaling procedures described in Section 2 to scale down the regional records through a range of yields down to 1 kt fully decoupled and added each of the scaled records back into the available noise record at each station. In particular, for each event we progressively reduced the effective yield by factors of two starting with the yield corresponding to the original explosion. To do this the elastic radius was reduced in succession by a factor of $\sqrt[3]{2}$ and used to recompute the scaling factor. Figure 6 shows the results of applying this sequence of scaling to the JVE explosion recorded at Urumchi. The original explosion magnitude was 6.0 m_b which corresponds to a yield of approximately 115 kt. Thus, the sequence of traces represents the series of approximate tamped explosion yields: 115 kt, 58 kt, 29 kt, 14 kt, 7.2 kt, 3.6 kt, 1.8 kt, 0.90 kt, 0.45 kt, 0.23 kt, 0.11 kt, 0.056 kt, 0.028 kt, 0.014 kt. Remembering that the maximum achievable decoupling factor is about a factor of 70, 0.014 kt tamped is approximately equivalent to a 1 kt fully decoupled explosion.

The source scaling procedure has a notable effect on the appearance of the regional phase signals in Figure 6. In addition to the pronounced reduction in amplitude (which is not apparent because the traces are individually scaled), the source scaling reduces the later arriving phases, including S_n, L_g, and R, relative to the P phases. This can probably be explained as a result of the stronger reduction of lower frequency signals at lower yields, which we saw above in Section 2 where we described effects of the scaling operation. In any case, this observation appears to indicate that, unless noise conditions are very low or stations are particularly close, it could be difficult to discern phases other than P from such small nuclear explosions at regional distances. This observation should have implications for discrimination as well as detection and location of such events.

The effect of adding the scaled records from Figure 6 back into the normal background noise at WMQ is illustrated in Figure 7. The signals for all regional phases are strong and well above noise at the higher yields. However,

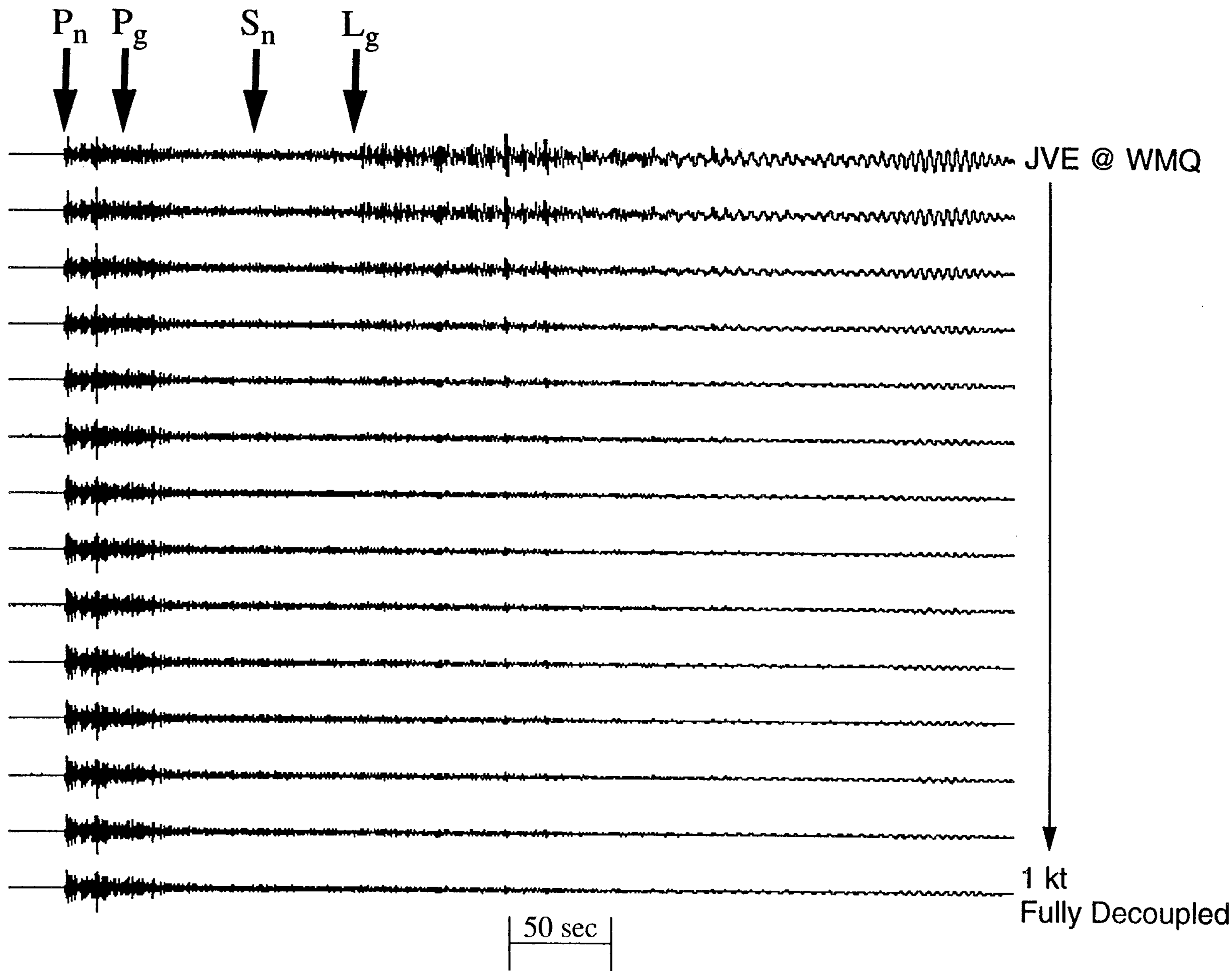

Figure 6. Synthetic regional seismograms obtained by applying the theoretical source scaling operators for successively lower yields to the station WMQ (R= 950 km) recording of the Soviet JVE.

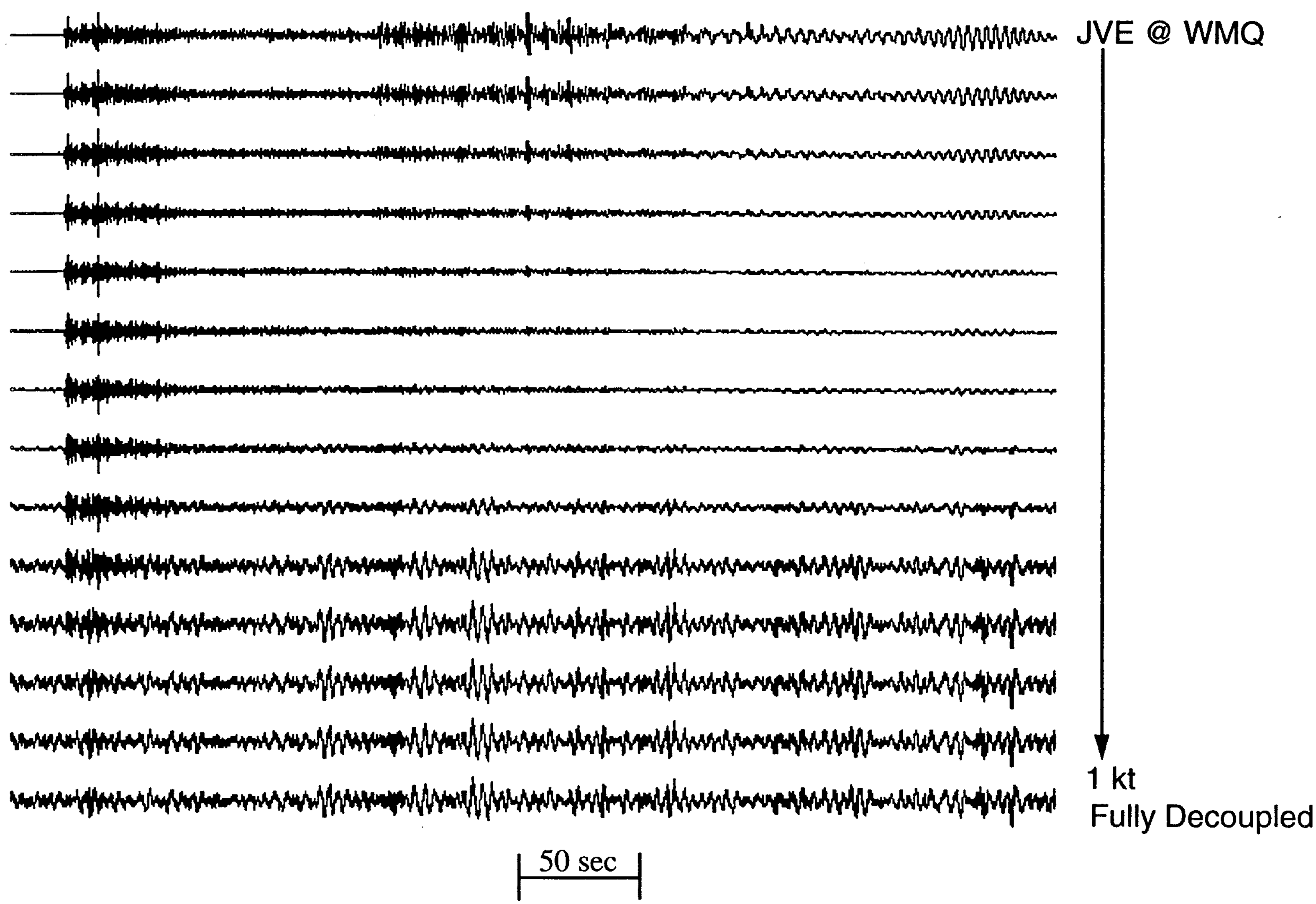

Figure 7. Synthetic regional seismograms obtained by re-embedding the scaled records of Figure 6 for the Soviet JVE at WMQ into seismic background noise from 09/14/88 at WMQ.

the signals begin to fall into the noise at lower yields. As we predicted from the behavior described above, secondary phases, like S_n, L_g, and R, fall below the noise level at much larger yields than do the regional P phases. The secondary phases generally appear to be at or below the noise on the broadband records for yields near 1 kt and below from tamped explosions at this station and range. The regional P phases are considerably stronger and are still apparent on the broadband records down to tamped explosion yields near 0.23 kt.

The regional signals clearly are not apparent on the broadband record at WMQ for the 1 kt fully decoupled explosion. To determine if such signals might be detectable in certain frequency bands, we again filtered the record using a series of narrow bandpass filters. The results, using the same set of filters as those applied above to the ARCESS records, are shown in Figure 8. The filtering process seems to do little to improve S/N. The transients near the expected L_g time in the frequency bands between about 0.5 Hz and 4 Hz appear to be noise; and what may be the P signal begins to appear at higher frequencies (viz. between about 3 Hz and 10 Hz), but in these high frequency bands there are noise bursts later in the records with amplitudes as large as those near the expected P arrival time. It should be noted that the sampling rate for these records is only 20 samples per second, so the output of filter passbands above 10 Hz have little validity. We also applied the bandpass filter analysis to the record corresponding to a tamped explosion with a higher yield of 0.11 kt, as shown in Figure 9. At this higher yield the S/N ratio is improved, but not dramatically. We see the same transients in the L_g window dominating the records at lower frequencies and possible evidence of S or other L_g in the 3 Hz to 10 Hz bands. Regional P phases are now better developed and are apparent over bands from about 1 Hz to 10 Hz.

Figures 10 and 11 show the same sequence of scaling procedures applied to the Soviet JVE explosion recorded at the IRIS station at Garm. The original explosion yield is again 115 kt, and we present the same sequence of scaled traces down to a tamped yield of 0.014 kt, or approximately 1 kt fully decoupled. We see about the same behavior here as we saw at WMQ. The overall amplitude reduction toward lower yields is accompanied again by a more pronounced decrease in the later arriving S_n, L_g, and R phases relative to P phases. One interesting feature apparent in Figure 10 is the change produced in the L_g/P ratio as the yield decreases. The broadband records show a transition in the L_g/P ratio from a value much greater than one (about

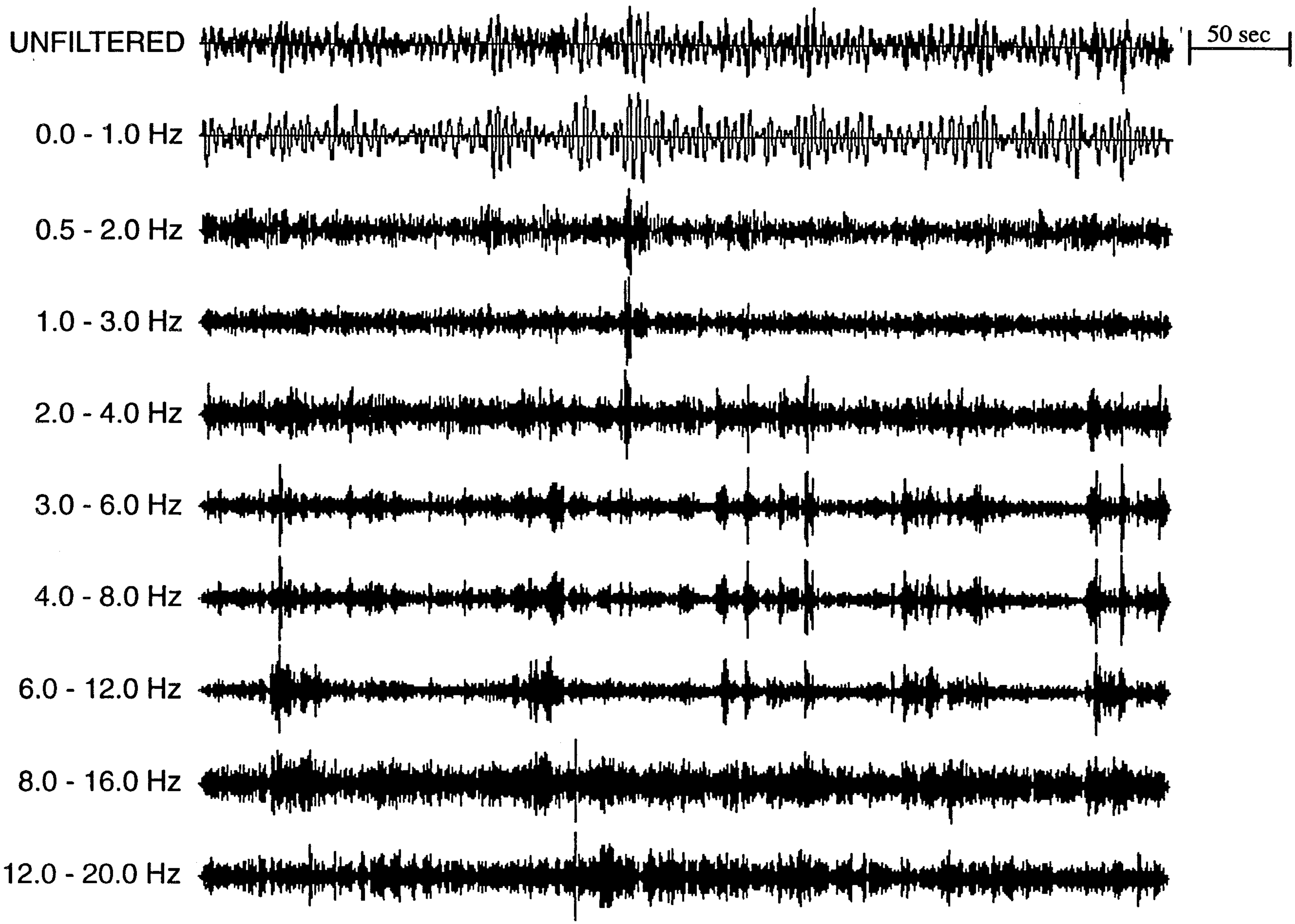

Figure 8. Application of bandpass filter analysis to the vertical-component WMQ recording of the 9/14/88 JVE explosion scaled down to 1.0 kt fully decoupled and embedded in noise.

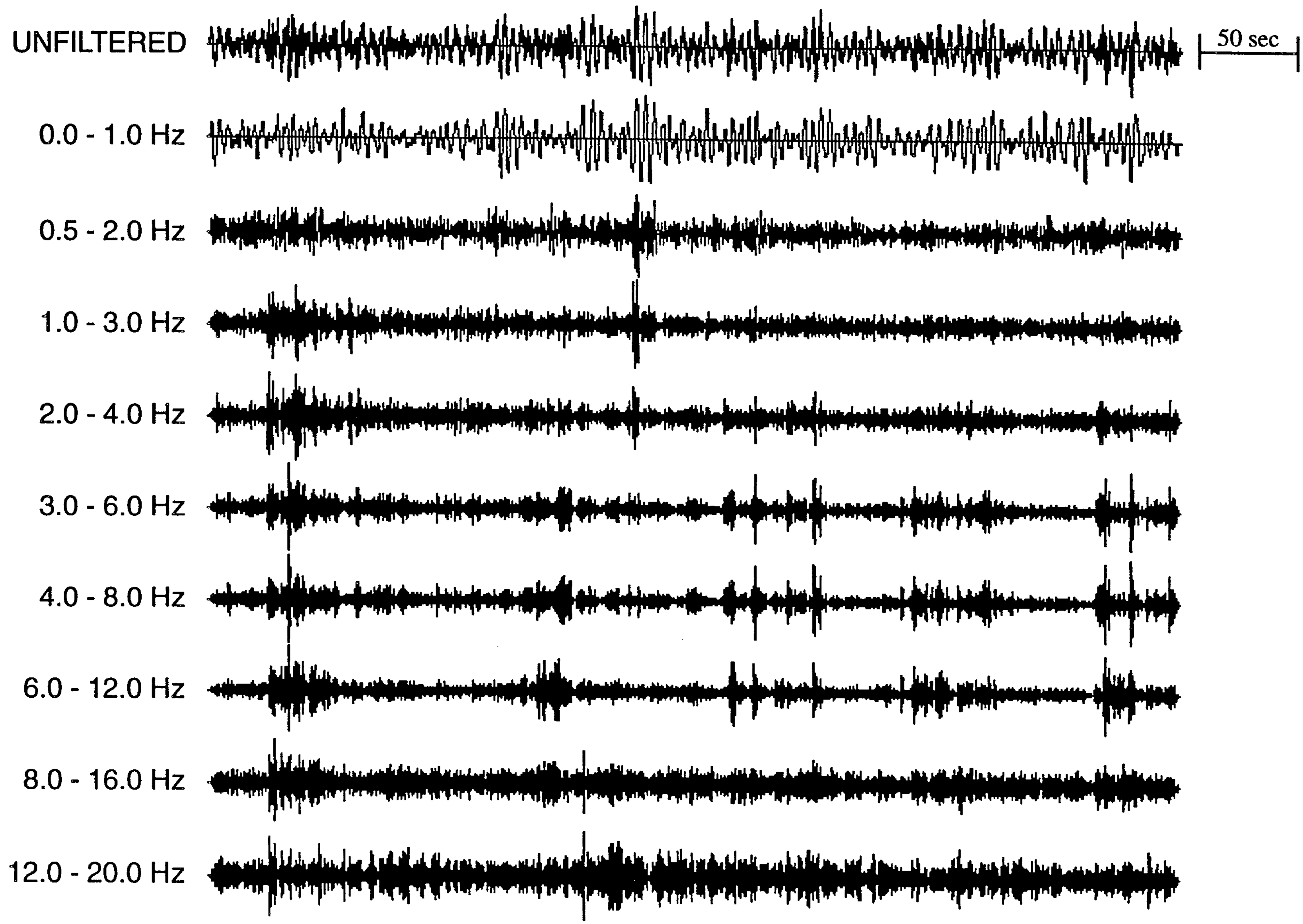

Figure 9. Application of bandpass filter analysis to the vertical-component WMQ recording of the 9/14/88 JVE explosion scaled down to 0.11 kt tamped and embedded in noise.

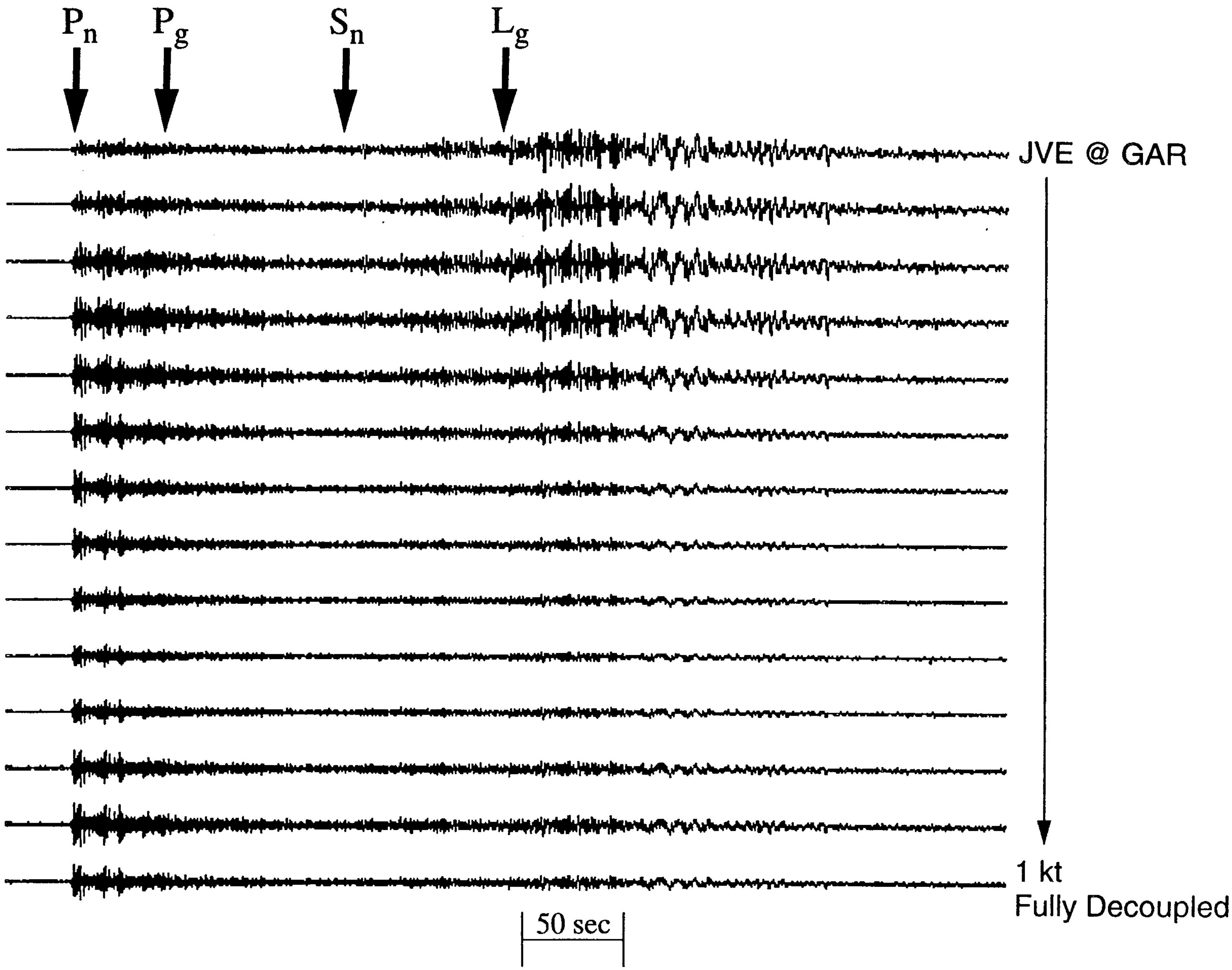

Figure 10. Synthetic regional seismograms obtained by applying the theoretical source scaling operators for successively lower yields to the IRIS station GAR (R = 1380 km) recording of the Soviet JVE.

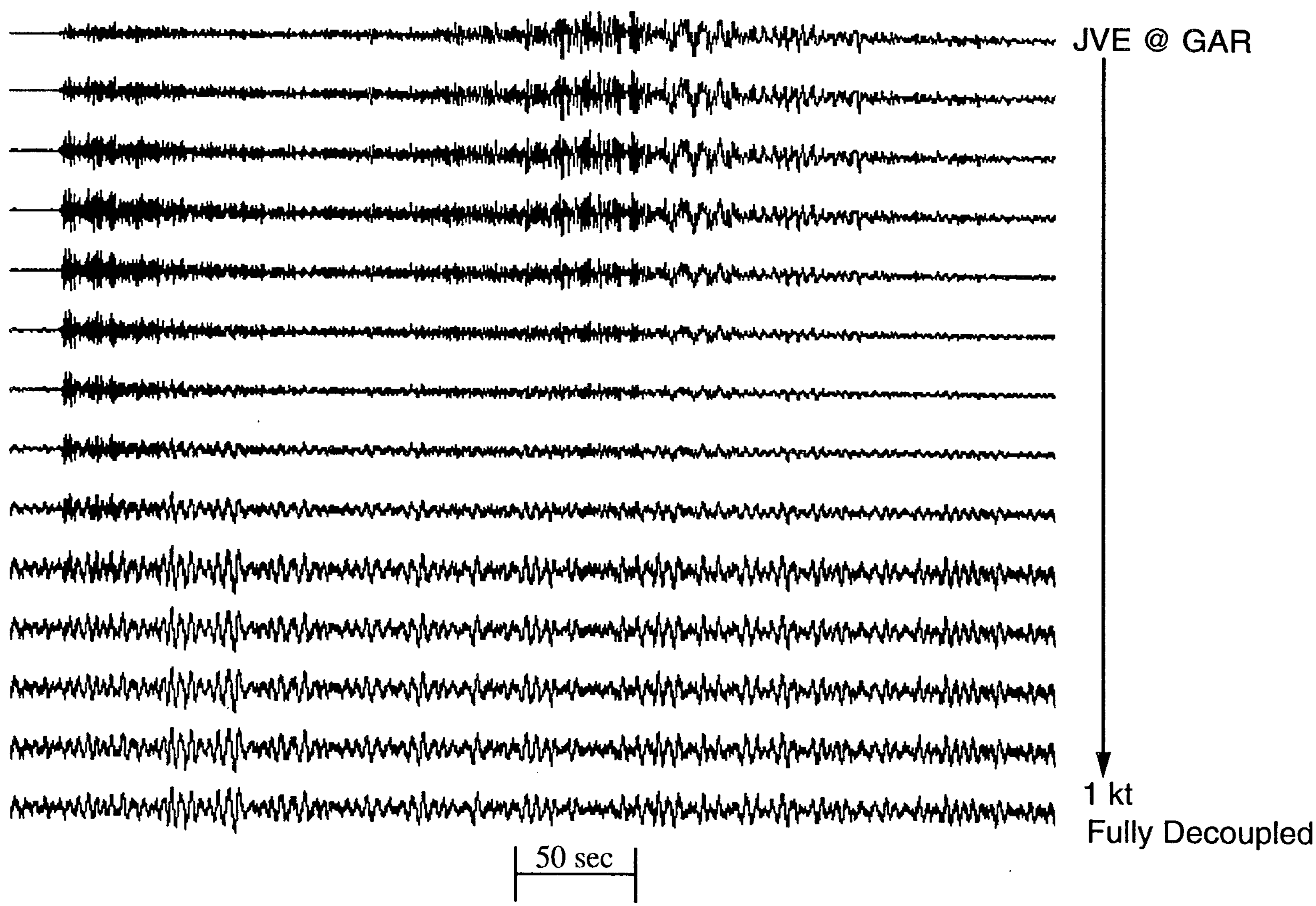

Figure 11. Synthetic regional seismograms obtained by re-embedding the scaled records of Figure10 for the Soviet JVE at GAR into seismic background noise from 09/14/88 at GAR.

2:1) at the high, original yield (115 kt) to a value much less than one (about 1:2) at the low yield (1 kt fully decoupled). A similar but less dramatic transition in the broadband L_g/P ratio was also evident in the source-scaled traces for the JVE at WMQ, shown above in Figure 6, where the L_g/P ratio went from a value near one to a value near four over the same range of yields. This result suggests that L_g/P ratio discriminants might perform better for smaller explosions. However, the predicted performance improvement would only hold up if the same dependence on magnitude was not seen in lower magnitude earthquakes. Furthermore, even if such differences can be verified, for purposes of discrimination it may be necessary to evaluate the ratio in multiple frequency bands covering a range of frequencies, considering the possible frequency dependence in the behavior of the ratio.

Figure 11 shows the signals from Figure 10 re-embedded in the background noise record at GAR from 09/14/88 (cf. Table 1, above). The behavior is similar to that described above at WMQ. At the higher yields the signals are strong for all regional phases. As we decrease the yield, the secondary phases, including S_n, L_g, and R, fall off more rapidly and disappear into the background noise for yields below about 1 kt. The regional P phase at GAR remains at or above the background noise down to a tamped yield near 0.11 kt. We again performed the bandpass filter analysis on the record corresponding to the 1 kt fully decoupled JVE at GAR and were unsuccessful; in no frequency band did the regional phase signals rise above the background seismic noise. Even when we ran the bandpass filter analysis on the record corresponding to a tamped yield of 0.11 kt (cf. Figure 12), we found little evidence of the regional signals. In some of the higher frequency bands the P signals seem to be just about at the noise level.

Finally, we applied the same scaling procedures to the 08/16/90 Chinese underground nuclear explosion at Lop Nor recorded at the IRIS station at Garm. Figure 13 shows a similar sequence of traces for decreasing yields after the scaled records have been re-embedded in the noise record for 08/16/90 (cf. Table 1, above). In this case the original yield for the Lop Nor explosion is estimated to have been about 215 kt, so the sequence of traces corresponds to scaled yields for tamped explosions of approximately 215 kt, 108 kt, 54 kt, 27 kt, 13 kt, 6.7 kt, 3.4 kt, 1.7 kt, 0.84 kt, 0.42 kt, 0.21 kt, 0.11 kt, 0.053 kt, 0.026 kt, and 0.014 kt, the latter again being equivalent to 1-kt fully decoupled. The regional P phases are clearly the dominant signals on the records at all yields. S_n

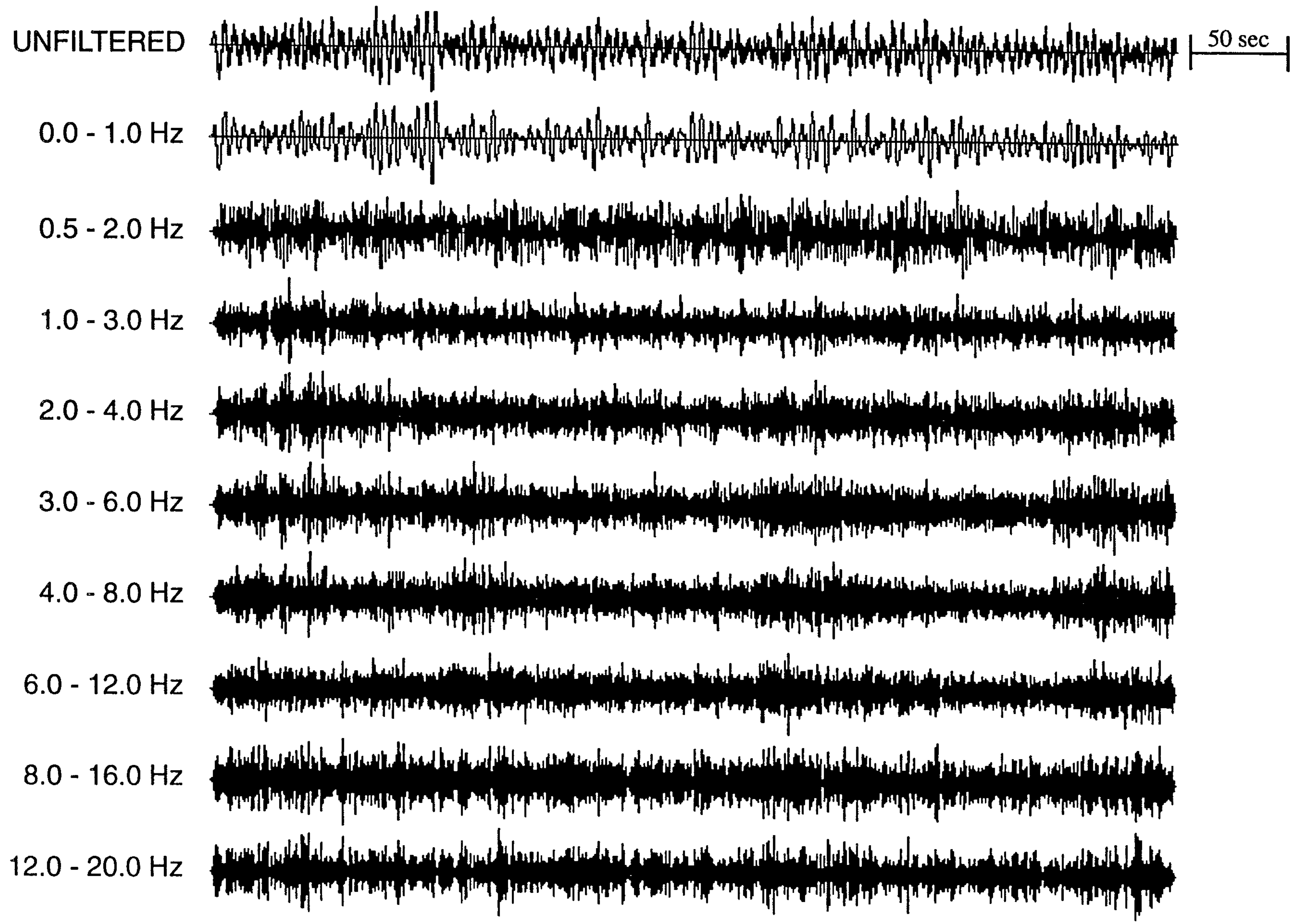

Figure 12. Application of bandpass filter analysis to the vertical-component GAR recording of the 9/14/88 JVE explosion scaled down to 0.11 kt tamped and embedded in noise.

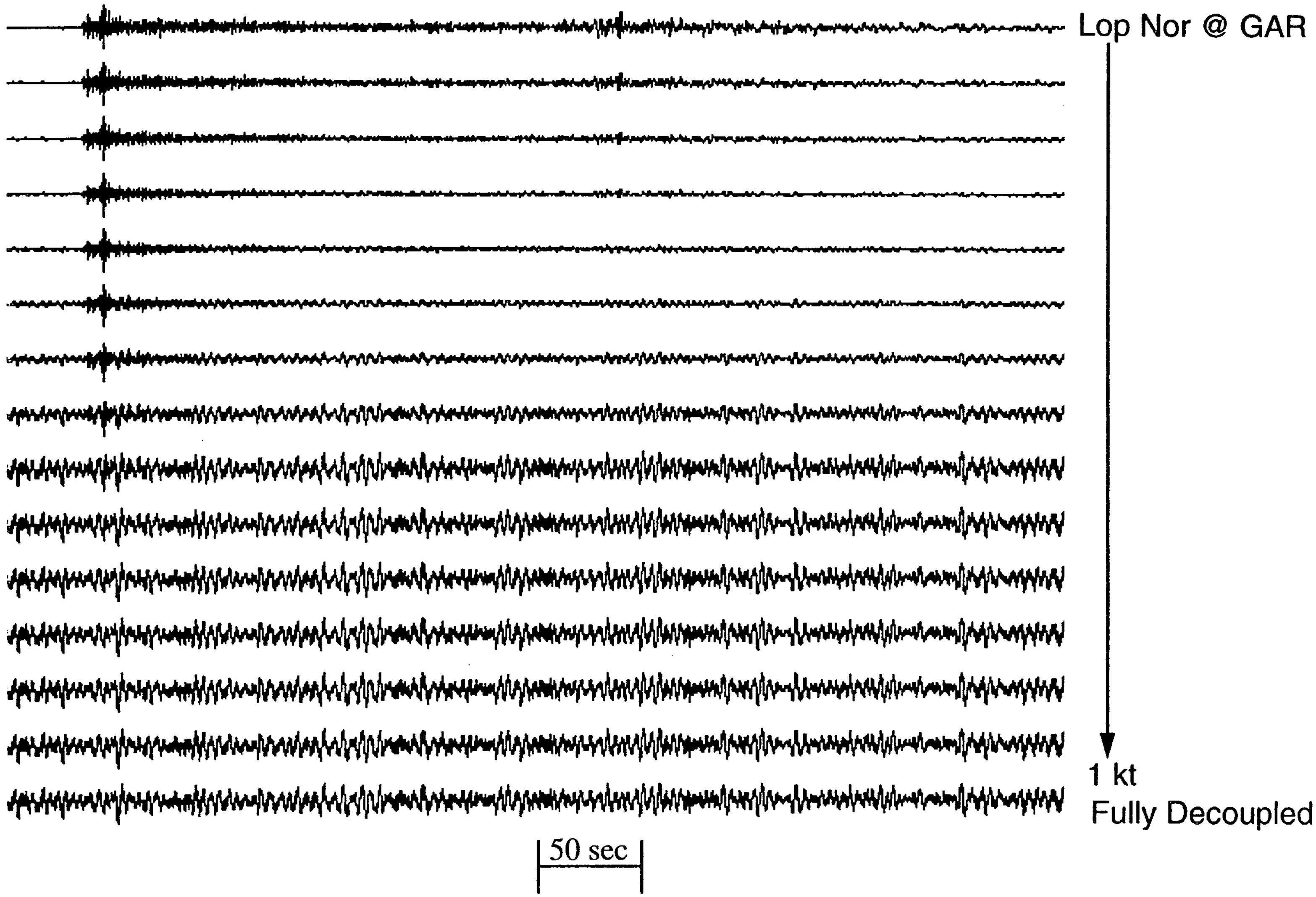

Figure 13. Synthetic regional seismograms obtained by re-embedding records for the 08/16/90 Lop Nor nuclear test recorded at GAR scaled to successively lower yields into seismic background noise from 08/16/90 at GAR.

signals are weak and not apparent even at high yields. L_g signals are apparent on the records at higher yields but rapidly disappear into the background noise as the yield is scaled to lower values. As a result, there is little evidence of secondary phases, including S_n, L_g, or R, below a tamped yield of about 5 kt on the scaled GAR broadband records from Lop Nor. The P phases again persist to somewhat lower yields, but fall into the noise on the broadband at about 1 kt fully tamped. We applied the bandpass filter analyses to the records simulating 1 kt fully decoupled and the higher yield of 0.11 kt tamped, but there was no evidence of any regional signals in any of the frequency bands at these yield levels.

The yield levels at which the scaled regional signals for the Lop Nor explosions disappear into the background noise here are considerably higher than those which we found above for the JVE nuclear test at WMQ (cf. Figure 7) and at GAR (cf. Figure 11). One explanation appears to be the higher noise level at GAR for the 08/16/90 date; the broadband noise level at GAR is about a factor of three higher on 08/16/90 than on 09/14/88. Another source of the discrepancy might be stronger attenuation or blockage along the Lop Nor-to-Garm path. This certainly seems to be a possibility for the secondary phases, considering that the L_g signals in Figure 13 are much lower amplitude than those in Figure 11 for similar yields while distances are not that much different. However, the situation is not so clear with the regional P phases which are roughly comparable in amplitude at similar yields. The relative influences of attenuation and noise levels on detectability and measurements of regional phase signals for seismic sources and stations in different regions clearly needs attention in assessing monitoring capability for small explosions.

4. Special Investigations of Small Regional Events Reported by the IDC

Over the past few years, numerous seismic events have been detected and reported by the prototype IDC operating at the Center for Monitoring Research (formerly CSS). Many of these events have been reported in the context of the Group of Scientific Experts Technical Tests (GSETT), but some have also been reported and analyzed at times when no technical tests were in progress. Many of the events are small, and some are in areas of relatively low natural seismicity. These are the kinds of events which are likely to require regional seismic monitoring for detection and identification. They are the kinds of events for which our scaled nuclear explosions, described above, can provide a useful comparison. We investigated two such events during the course of this contract: (1) the 12/31/92 event at NZ, and (2) the 01/05/95 event in the Ural mountains of Russia. We will review here some aspects of the 12/31/92 NZ event, which were discussed by Bennett et al. (1993, 1994a), and then describe in more detail the regional discrimination analyses which we performed on the 01/05/95 Urals event.

4.1 The Novaya Zemlya Event of December 31, 1992

An event of unknown origin occurred on 12/31/92 in the vicinity of the Russian nuclear test site at Novaya Zemlya (cf. Ryall, 1993). The event was located at 73.5 N, 55.5 E and had an origin time of 09:29:25 GMT. NORSAR reported the magnitude of this event as 2.5 m_b. The small magnitude of this event and its location in an area which is naturally aseismic but has been the site of prior nuclear tests make this the kind of event which might raise concern under a CTBT as a possible decoupled nuclear explosion test. Seismic signals from this event were recorded mainly at the ARPA regional array stations at ARCESS and NORESS and by seismic stations on Spitzbergen island to the west; other stations were generally too noisy to be useful at this low magnitude level.

In our original analysis of this event (cf. Bennett et al., 1993) we bandpass filtered the records at ARCESS from the 12/31/92 unknown event at NZ and the original, unscaled records from the 10/24/90 NZ nuclear explosion which had a magnitude of 5.7 m_b. We also compared bandpass filter records at NORESS from the same 10/24/90 NZ nuclear explosion with the records from a

4.7 m_b earthquake near NZ. For the filters we used passbands of 2-4 Hz and 8-16 Hz. At ARCESS we found that in the lower frequency band the 12/31/92 event and the nuclear explosion both produced S/P ratios near one; but in the higher frequency band the S/P ratio was much higher for the 12/31/92 event than for the nuclear explosion. The earthquake at NORESS also produced a somewhat higher S/P ratio than the explosion, and the differences tended to be enhanced in the high frequency band.

In our current analysis we used the records developed from the scaling procedure for comparison. In particular, we can use the simulated ARCESS record for a 1 kt fully decoupled explosion to compare to the ARCESS record for the 2.5 m_b 12/31/92 NZ event. The corresponding events are of nearly the same size, and the propagation paths to ARCESS are essentially identical. We performed a more complete bandpass filter analysis on the center-element, vertical-component records at the ARCESS array from the events. Figures 14 and 15 show the results of the band-pass filter analyses on respectively the 12/31/92 unknown event and the 10/24/90 NZ explosion scaled to 1 kt fully decoupled and added back into background noise. Below about 3 Hz we see little evidence of regional signals for either the 12/31/92 NZ event or for the simulated low-yield nuclear explosion. In higher frequency passbands P_n and S_n signals are apparent for both events, but there is little indication of L_g for either. The S_n signal and its coda appear to be better developed for the 12/31/92 event. For frequency bands between about 3 Hz and 16 Hz, we see that S/P ratios for the 12/31/92 event are greater than 1.0. In contrast, over the same bands the maximum S/P ratios for the 10/24/90 NZ explosion scaled to 1 kt fully decoupled are only about 0.5.

We would interpret this result to indicate that the 12/31/92 unknown event at NZ has far-regional signal characteristics at ARCESS different from what would be expected from a small underground nuclear explosion of approximately comparable magnitude. In other parts of the world investigations (cf. Bennett et al., 1992; 1994b) have shown that the S/P or L_g/P ratios from earthquakes and certain other non-explosion sources (e.g. rockbursts) tend to maintain a level at or above 1.0 over a broad band out to high frequencies while similar ratios for explosions tend to drop off rapidly to well below 1.0 at high frequencies. Thus, the behavior we see in Figure 14 for the relative amplitude of the regional S and P signals as a function of frequency would be consistent with interpretation of the 12/31/92 event as an earthquake.

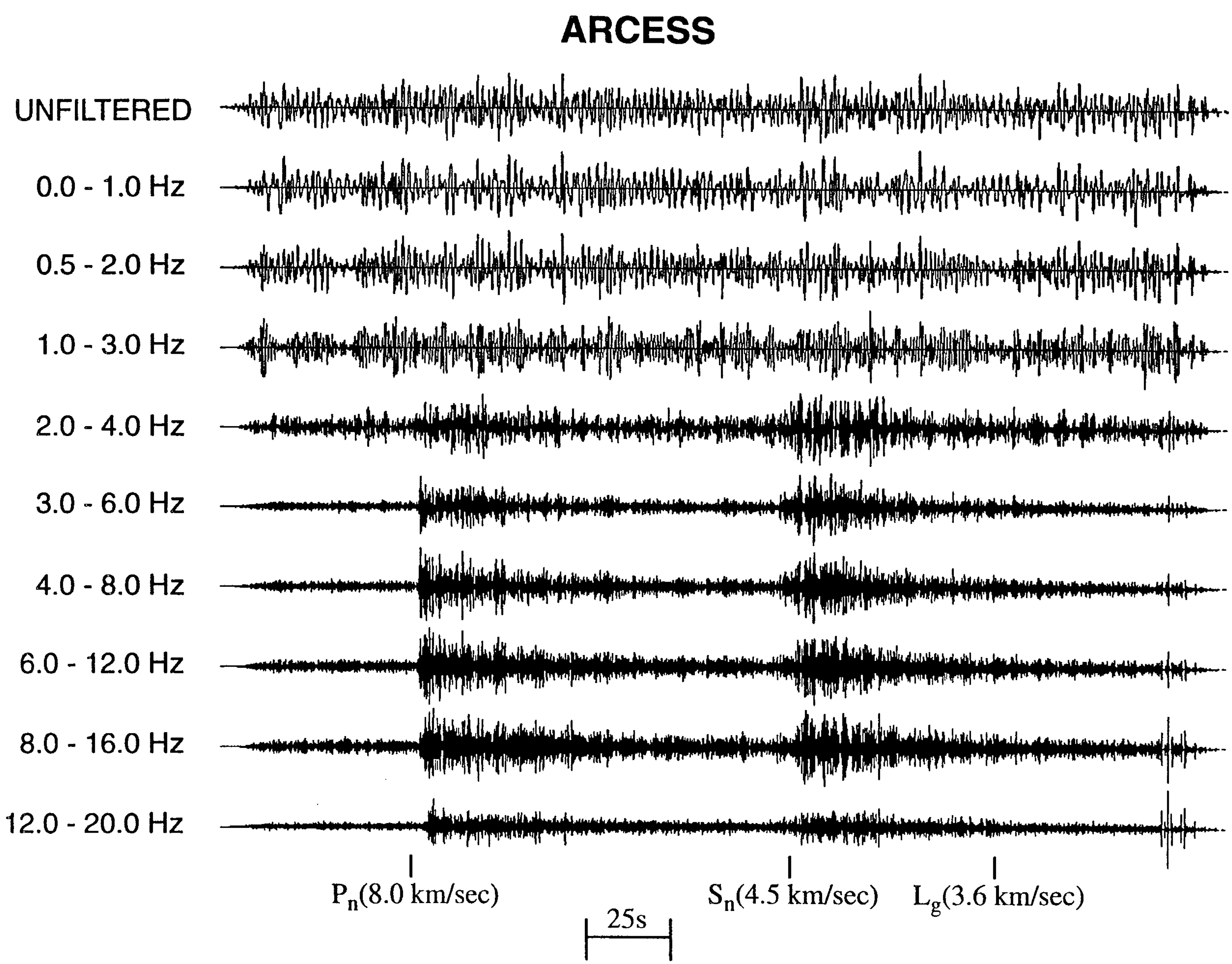

Figure 14. Application of band-pass filter analysis to vertical-component ARA0 recording of the 12/31/92 unknown event at Novaya Zemlya.

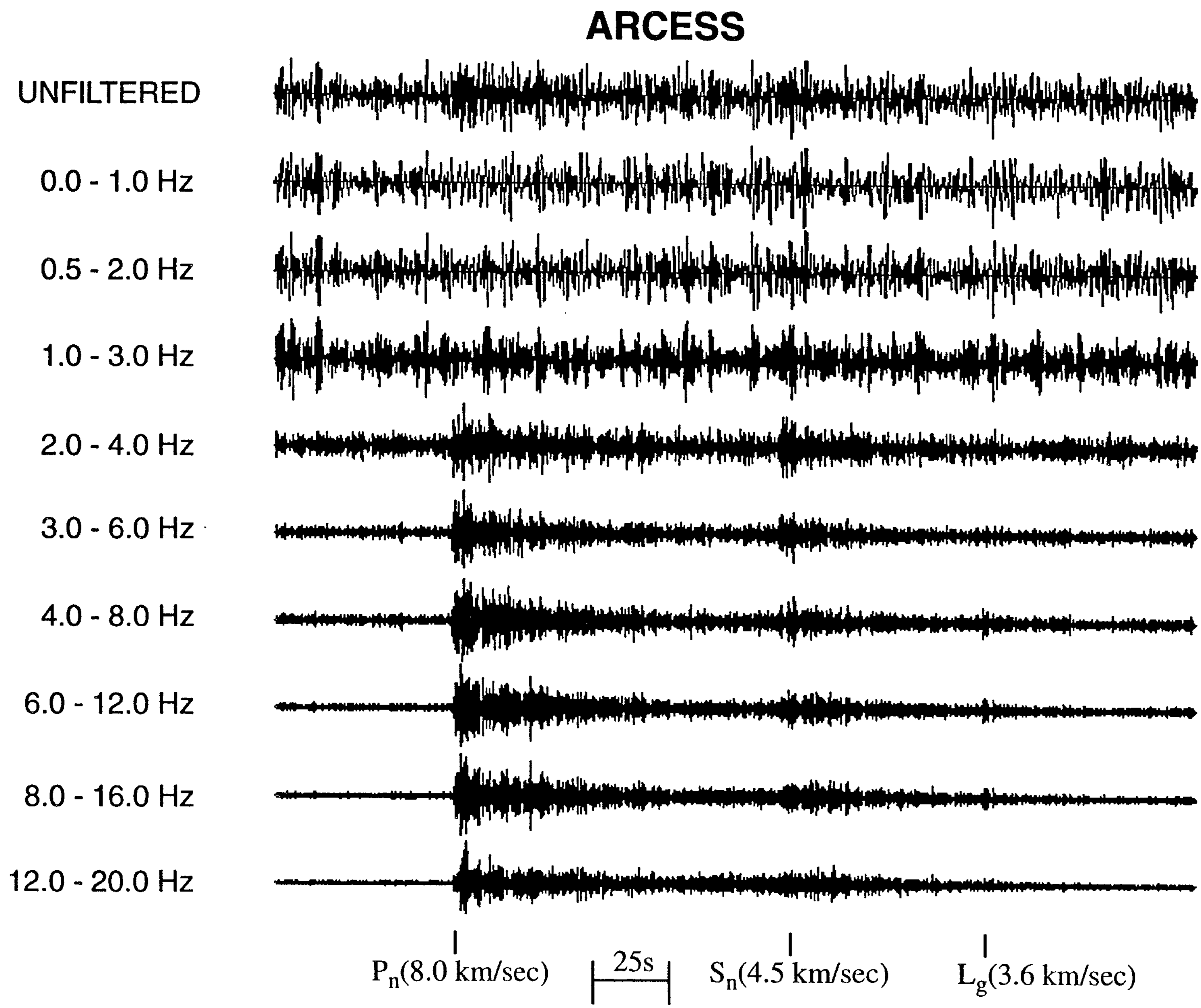

Figure 15. Application of band-pass filter analysis to vertical-component ARA0 recording of the 10/24/90 NZ explosion scaled down to 1kt fully decoupled.

4.2 The Ural Mountains Event of January 5, 1995

Another test of seismic regional monitoring was provided by the 01/05/95 event in the Ural mountains of Russia. The event occurred in an area of low natural seismicity (cf. Figure 16). However, a number of Russian PNE's have been located in the vicinity of the Ural mountains (including seven within about three degrees of the epicenter); and there is mining activity in the general source area of this event. The epicenter of the 01/05/95 event was located by the IDC at 59.52 N 56.31 E, and the IDC reported a magnitude of 4.35 m_b while the PDE magnitude was 4.7 m_b. Although this event was located somewhat beyond the normal regional distance range from the Scandinavian ARPA regional arrays, regional S and L_g signals are apparent on the records at FINESS ($R \approx 1660$ km), ARCESS ($R \approx 1820$ km), and NORESS ($R \approx 2450$ km). Good regional signals from this event were also reported at closer seismic stations in Russia, and we have focused on these in our investigations. In particular, the IRIS station at ARU was located about 360 km from the source and IRIS station OBN was about 1280 km from the source (cf. Figure 16).

We performed a bandpass filter analysis on the vertical-component record at ARU for the 01/05/95 event. The results of the analysis are shown in Figure 17. The filtered traces show a strong R_g phase in the 0.5-2.0 Hz passband. Such strong R_g excitation is considered to be indicative of a shallow source. At frequencies lower than about 3 Hz, the L_g/P ratios are observed to be large (much greater than one); but above 3 Hz the S/P ratios are only about one. In fact, over a limited band from 3 Hz to 6 Hz, the S/P ratio appears to fall well below one before increasing again in higher frequency bands. We also see in the bandpass filter results that the P phases are rather simple in appearance and quite impulsive, particulary for some of the higher frequency bands.

As noted above, this region of Russia is one of fairly low natural seismicity; so there are no regional records of seismic sources from this area which can be used for comparison with the ARU record for the 01/05/95 event. For comparison we decided to use the records from three western European events, of different source types, which were located at about the same epicentral distance from station GRFO as the 01/05/90 event was from ARU. The three events recorded at GRFO included a magnitude 4.3 m_b earthquake in the Netherlands ($R = 387$ km), a magnitude 4.0 m_b Polish rockburst ($R = 390$ km), and a Swiss munitions blast ($R = 393$ km) with a magnitude of 4.2 m_b. The

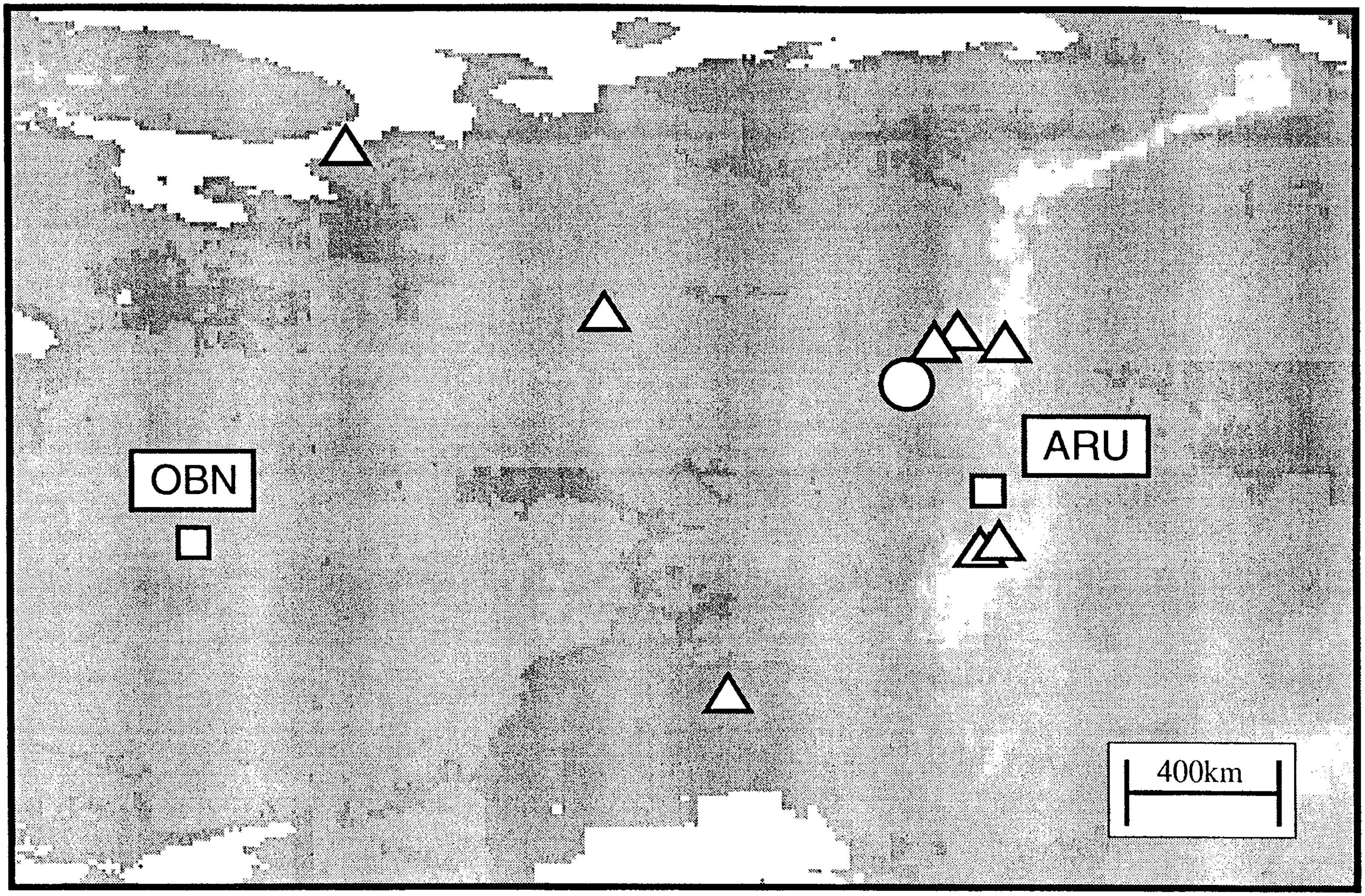

Figure 16. Locations of the 01/05/95 Urals event (◯), seismicity of the past decade reported by NEIS (△) , and regional seismic stations (□) used in analysis.

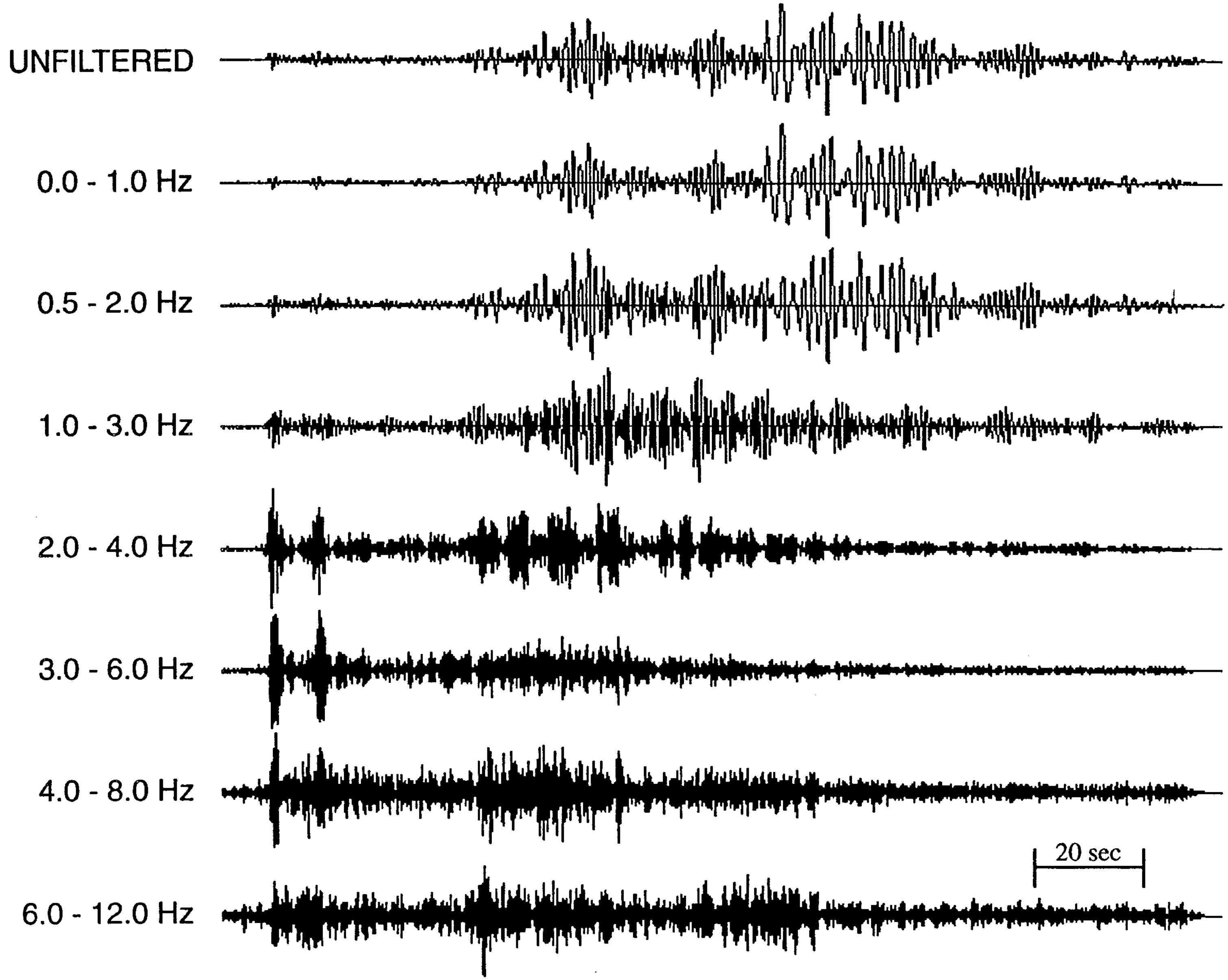

Figure 17. Bandpass filter analysis of the ARU record for the Urals event of January 5, 1995. Note an instrument correction has been applied to make the response equivalent to GRFO.

instrument response at ARU in Figure 17 was modified to be equivalent to GRFO to enable more direct comparisons of the regional signals. So, the events we are using for comparison have about the same magnitudes, the recording instrument responses have been made equivalent, and the epicentral distance is roughly comparable, although the propagation characteristics between the regions admittedly may be different. To make the comparisons we performed the same bandpass filter analyses on the records from the three events. The results of the bandpass filter analyses are shown in Figures 18 - 20. The noise spikes falling in the L_g window at higher frequencies in Figures 18 and 20 are of unknown origin but are clearly unrelated to real signals and should be disregarded. 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 are seen to be greater than one for the Polish rockburst at lower frequencies (below about 3 Hz) and about one at higher frequencies, as we also saw for the Urals event. Although the earthquake also has large L_g/P or S/P at most frequencies, the energy there appears to be more dispersed across the different phase windows. The munitions blast analysis shows generally smaller L_g/P, particularly at frequencies near 1 Hz where the blast signals showed a strong P_g phase.

There are some far regional data available from the Scandinavian ARPA array stations for the 01/05/95 Urals events which could be compared with similar recordings of PNE's scaled down to the lower magnitude levels using the procedures described in the previous sections of this report. The S/N levels for these records are generally lower, and the regional signals with adequate S/N tend to be more band limited. We have not yet attempted such scalings and comparisons for these additional data.

Independent of the analysis shown here, we also looked at characteristics of the long-period surface waves from this event recorded at the same nearer regional IRIS stations. Based on analysis of the longer-period bands in the surface wave window, a single station M_S of 3.38 was measured for the Urals event at station OBN (cf. Stevens, 1995). This single station M_S measurement would appear to be low (by about one magnitude unit) relative to the m_b reported for this event, but more thorough analyses of the long-period surface-wave excitation at this and other stations from this event should probably be performed to confirm this result. Observations of M_S which is weak

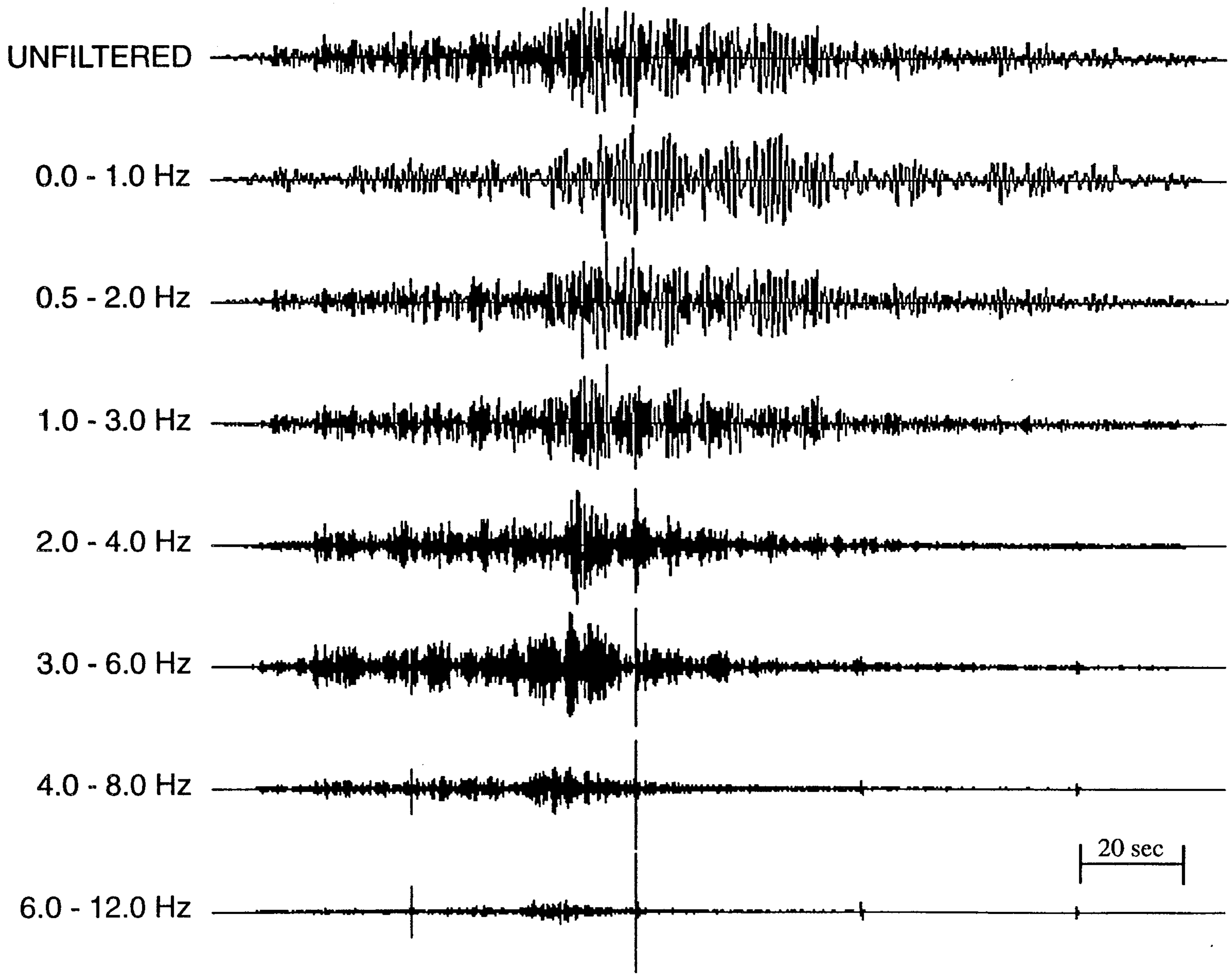

Figure 18. Bandpass filter analysis of the Netherlands earthquake of April 14, 1992 recorded at GRFO (R = 387 km).

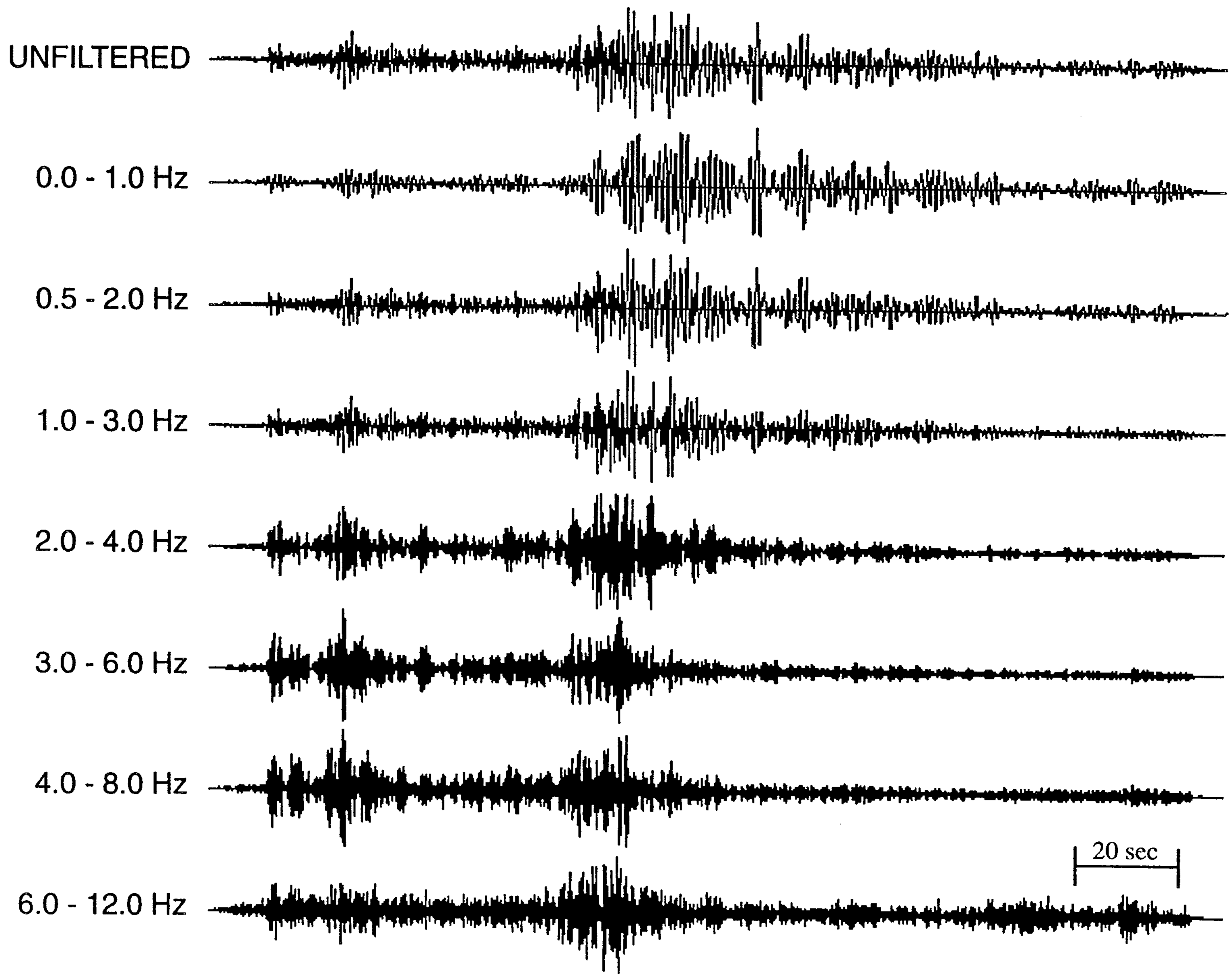

Figure 19. Bandpass filter analysis of the Polish rockburst of August 15, 1981 recorded at GRFO (R = 390 km).

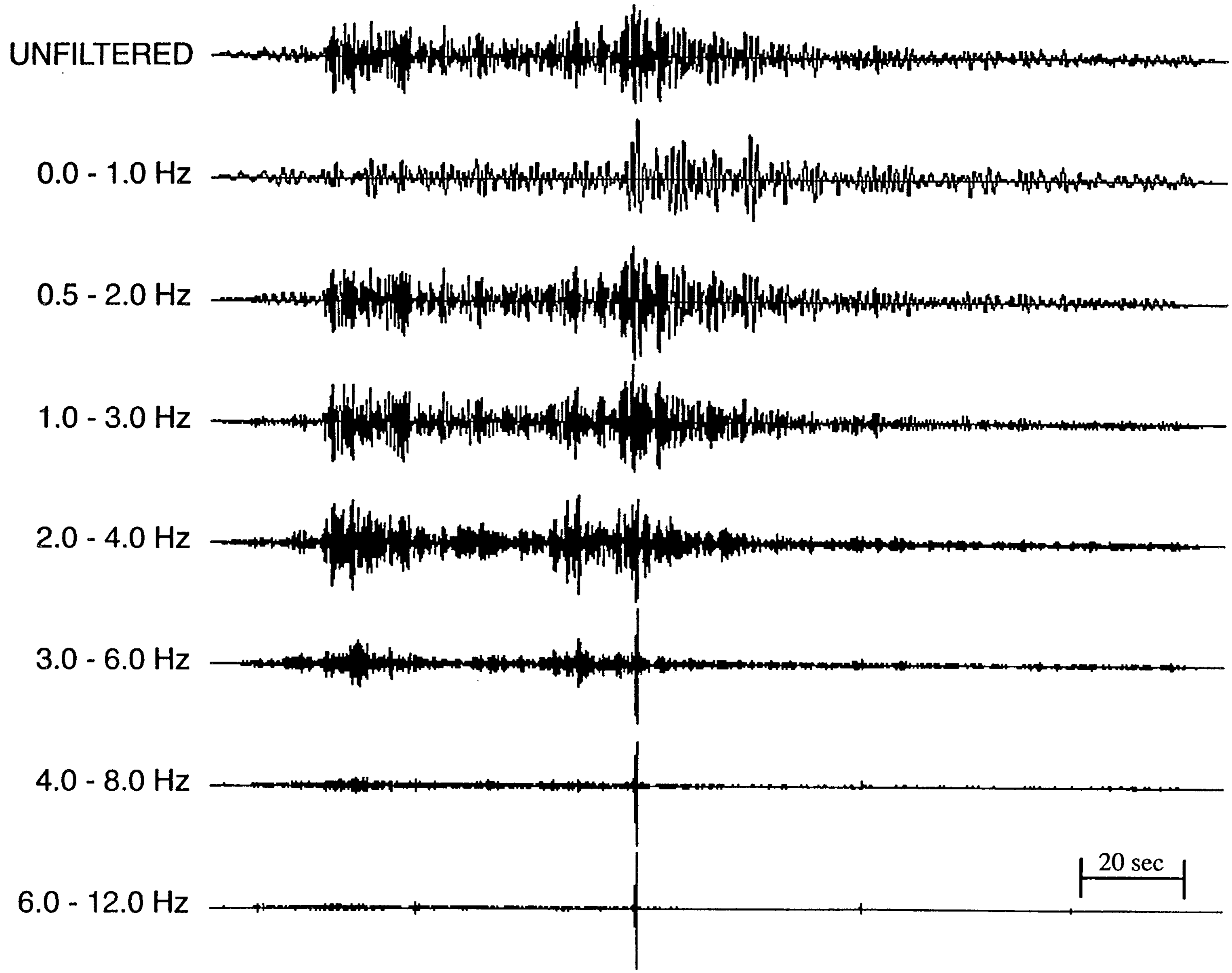

Figure 20. Bandpass filter analysis of the Swiss munitions blast of November 2, 1992 recorded at GRFO (R = 393 km).

relative to m_b are typical of explosion sources, but such behavior is also frequently seen in rockbursts (cf. Bennett et al., 1994b).

Based on these observations at the Russian stations ARU and OBN, we conclude that the 01/05/95 Urals event was clearly shallow considering the strong R_g phase. Considering that most earthquakes tend to be deeper, the strong R_g phase could be indicative of a non-earthquake source. The relatively weak M_S observed for the 01/05/95 event is 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, i.e. one or above in most frequency bands over a fairly broad band. This behavior is consistent with behavior seen in other parts of the world for rockbursts and earthquakes but does not agree with explosion observations (cf. Bennett et al., 1992; 1994b). Based on these observations we conclude that the 01/05/95 Urals event was most likely a rockburst. This conclusion appears to be supported by the fact that the event occurred in an area of known below-ground mining and by damage reports from a Russian mine in the vicinity of the epicenter.

5. Summary and Conclusions

Systematic regional seismic monitoring extended on a global scale is likely to find large quantities of small seismic events which would require characterization under a CTBT. Monitoring experience with the prototype IDC operating at the ARPA CMR confirms the need for sound and efficient regional techniques for detection, location, and identification of small seismic events. Current capability for regional seismic monitoring of these events lacks the assurance which has traditionally been associated with teleseismic monitoring of large events using global networks. The goal of this research program has been to help to improve regional seismic monitoring capability for small events. In particular, we have sought to enhance understanding of the behavior of regional signals from small underground nuclear explosion tests which might aid their characterization. To accomplish this objective we have applied theoretical explosion source scaling procedures to modify the observed regional signals from larger explosions. We then re-embedded the scaled signals in normal seismic background noise and assessed how this might affect detection, location, and identification procedures. In a related study we performed regional seismic identification analyses on two small specific events in Eurasia which were detected by the IDC and provide an interesting test of monitoring capability at low magnitude levels.

To simulate regional signals from small nuclear explosions, Mueller-Murphy explosion source scaling was applied to observed regional seismograms from several large nuclear explosion tests at NZ and a large PNE in northwestern Russia recorded at the ARPA regional array stations in Fennoscandia. Similar scaling procedures were applied to the Soviet JVE explosion at Balapan and a Chinese nuclear explosion test at Lop Nor. For these latter events we used the records from high-quality digital stations at IRIS station GAR and CDSN station WMQ in the reginal distance range. The original seismic records were scaled down to simulate the signals from a 1 kt fully decoupled underground explosion, as well as intermediate yields. The scaled regional signals were embedded in representative background noise at the regional stations, and the simulations were then used to assess the limitations on detection and identification capabilities of regional signal analysis methods at the lower thresholds. We analyzed time-domain amplitude and spectral behavior of the scaled signals relative to representative samples of background noise to determine signal-to-noise levels and to identify limits on the frequency bands of regional signals which are likely to be useful for regional discrimination of small events.

As part of our initial effort with the observations from the Scandinavian ARPA regional arrays, a digital data tape was also provided to the Center for Monitoring Research for use in testing capabilities of the monitoring system for small events. The data tape included full-array data obtained by applying the source scaling procedures to three different events and, then, reintroducing the scaled signals into two different long segments of representative background noise. Our more recent work has focused on extending the procedures to explosion sources in other regions where we could only use non-array recordings.

An important finding based on these simulations is that the seismic signals from nuclear explosions at a threshold level near 1 kt fully decoupled could be difficult to discern on broadband records at far-regional stations. In fact, our scaling results suggest that for some far-regional stations it might be difficult to detect explosions with significantly larger yields due to higher levels of background noise or increased attenuation. Our bandpass filter analyses of the simulated records indicate that the useful signals from such small or decoupled explosions may be constrained to rather limited high-frequency bands. We found for ARCESS that, even at times when the background noise level may be low and regional signals are visible on the broadband records, the signals may still be restricted to higher frequency bands. At farther regional distances attenuation is also likely to play a role in limiting the high-frequency content of regional signals. These kinds of limitations would tend to restrict the available frequency band of regional phases for use in detection, location, and discrimination of seismic events. Some regional discrimination techniques may be impaired more than others by such frequency limitations (e.g. techniques which compare regional signal properties over a broadband may not be applicable). Although array processing techniques are likely to provide some improvement in overall signal detectability, we have not here specifically considered how such procedures might affect these conclusions. Further work is also needed to refine the character of the frequency-band limitations and their influences on various discriminant measures and regional detection and location capabilities for different regions and stations of interest.

It follows directly from the source scaling theory used in our analyses that, as explosion levels of interest are shifted to lower yields, the frequency content of the regional signals is shifted to higher frequencies. This not only affects the useful frequency band, but we also found evidence that it may cause variations in the L_g/P or S/P ratio, which is often used as a regional discriminant measure. We saw a tendency in the ratio to decrease at lower yield. While this dependence tends to make lower-yield explosions appear more explosion-like, the discriminant itself might not be enhanced unless the corresponding earthquake spectra scale differently than explosions for lower magnitudes.

Finally, with regard to specific small events detected by the IDC, we performed regional discrimination analyses on two events: (1) an unknown event at Novaya Zemlya on 12/31/92, and (2) an event in the Ural mountains of Russia on 01/05/95. Comparison of bandpass filter results from the 12/31/92 unknown event at Novaya Zemlya and from the simulation of a 1 kt fully decoupled explosion at the common ARCESS recording station indicates a larger S/P ratio for the unknown event at high frequencies (above about 3 Hz). These differences appear to be associated with more high-frequency P-wave energy in the explosion source. Based on these comparisons the 12/31/92 unknown event at NZ is considered to be more typical of an earthquake. For the 01/05/95 Urals event, the strong R_g indicates a shallow focus not usually seen in earthquakes, the weak M_S relative to m_b is more typical of explosions or rockburst, and large L_g/P and S/P ratios over a range of frequencies is normally seen in earthquakes or rockbursts but not explosions. We, therefore, concluded that the event was most likely a rockburst or mine tremor, which appears to be supported by evidence of damage at a mine near the epicenter.

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