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REGIONAL SEISMIC DETECTION ANALYSES OF SELECTED SOVIET PEACEFUL NUCLEAR EXPLOSIONS

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Seismic detection of small, evasively tested underground nuclear explosions remain as a major challenge to effective verification of any eventual CTBT. Most seismic detection research reported to date has focused on analyses of regional seismic signals recorded from explosions at the few known nuclear weapons test sites and, consequently, represent only limited ranges of the source and propagation path conditions of potential monitoring interest. In this study, we analyze regional seismic data recorded at the Borovoye station in Central Asia from a selected group of Soviet PNE tests which sample wider ranges of the source and propagation path variables of interest. The results of these analyses have indicated that it will in general be difficult to seismically detect low-yield, cavity decoupled nuclear explosions, even with high quality stations at regional distance of 10° or less, and that additional research will be required to optimize the seismic networks and signal processing systems needed to monitor such clandestine tests.

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1. INTRODUCTION

A central issue which needs to be addressed in assessing the seismic monitoring capability required to adequately verify any eventual Comprehensive Test Ban Treaty (CTBT) concerns the definition of the threshold level of explosion yield down to which seismic events will have to be detected and identified. For example, since it has been experimentally demonstrated that it is possible to reduce the amplitude of the radiated seismic signal of an underground nuclear explosion by at least a factor of 70 by employing the cavity decoupling evasion scenario, it follows that a truly comprehensive monitoring of underground nuclear tests down to the 1 kt level will require the detection and analysis of seismic signals corresponding to fully tamped nuclear explosions with yields of about 14 tons. However, it is difficult to directly assess the detectability of such small nuclear tests, since there are no regional seismic data available which have been recorded from nuclear explosions in this yield range. Moreover, most of the seismic detection research which has been conducted to date has focused on analyses of regional seismic signals recorded from explosions conducted at the few major nuclear weapons test sites and these events sample only limited ranges of the source and propagation path conditions which will have to be considered in monitoring a global CTBT.

In an attempt to overcome these limitations of previous analyses, S-CUBED has been working with scientists from the Russian Institute for Dynamics of the Geospheres (IDG) to use regional seismic data recorded from the extensive Soviet Peaceful Nuclear Explosion (PNE) testing program to better quantify the detectability of small evasively tested underground nuclear explosions. Over 120 tests were conducted in this PNE series and these explosions were detonated in a wide variety of geologic emplacement media (e.g., salt, clay, sandstone, granite, limestone) and are representative of wide ranges in yield (0.01 to 300 kt) and source depth (130 to 2860 m). Furthermore, because of the tremendous geologic and tectonic diversity present within the territories of the former Soviet Union, regional seismic data recorded from these tests sample propagation path characteristics encompassing a range extending from tectonically active to stable continental interior regimes. In order to quantitatively assess the seismic detectability of evasively conducted underground nuclear tests corresponding to these varied source and propagation path conditions, regional seismic data recorded from selected Soviet PNE tests at the Borovoye digital station in Central Asia have been theoretically scaled to obtain estimates of the corresponding seismic signals to be expected from small cavity decoupled nuclear explosions at those same source locations. Comparisons of these simulated regional seismic signals with various estimates of background noise conditions then provide estimates of the frequency dependent detectability of such evasively conducted underground nuclear tests for more representative ranges of source and propagation path conditions than those considered in previous investigations of this problem.

This report presents a summary of the research investigations conducted under this study program. The characteristics of the selected Soviet PNE tests are described in Section 2, together with the regional seismic data recorded at the Borovoye station from these explosions. This is followed in Section 3 by the presentation of a detailed detection analysis conducted using simulated regional seismic data derived by theoretically scaling these observed Borovoye data to simulate the corresponding data which would be expected from low yield cavity decoupled nuclear tests at the selected PNE locations. The report concludes with Section 4 which contains a summary and statement of conclusions regarding the seismic detectabililty of small underground nuclear explosions, evasively tested under a variety of source, station and propagation path conditions representative of those which might be encountered in global CTBT monitoring.

2. SOVIET PNE DATA

From its inception in the mid 1960's, the Soviet PNE program utilized nuclear explosions in a variety of commercial and scientific applications. Over 120 explosions were conducted in this series up until its cessation in 1988 and the locations of these tests were widely dispersed throughout the territories of the former Soviet Union. The majority of these tests can be roughly grouped into three areas of application: stimulation and control of oil, gas and mining extraction processes (29 events), creation of underground storage cavities, primarily in salt (38 events) and deep seismic sounding (38 events). The remaining few events were devoted to a variety of purposes, including excavation of near surface materials for construction projects and development of repeatable seismic sources for applications in geophysical exploration and earthquake hazards studies. These explosions were conducted in a wide variety of geologic emplacement media and are representative of broad ranges in yield and source depth. As such, they represent a unique resource for use in seismic verification studies of underground nuclear testing.

Teleseismic data recorded from a large number of these Soviet PNE tests have been analyzed in previous studies (e.g., Murphy and Barker, 1994), but only limited data recorded in the regional distance range have been available until quite recently. Over the past several years, Sultanov and his colleagues at the Russian IDG have begun to digitize some near-regional, photographic recordings from selected PNE tests and these data have been incorporated into analyses of the seismic source characteristics of a number of underground nuclear explosions (e.g., Murphy *et al.*, 1996). In addition, data recorded at the Borovoye digital seismic station in Central Asia from a number of Soviet nuclear tests have now been made available by the IDG (Adushkin and An, 1990; Laushkin *et al.*, 1995) for analysis by the seismic verification community. The Borovoye Geophysical Observatory is located in North Kazakhstan (53.08°N, 70.25°E) and is one of the oldest digitally recording seismic observatories in the world, having initiated digital recording in 1966. A variety of long-period and short-period seismic systems have been deployed at this station over the years (Kim and Ekström, 1996), including some relatively broadband systems which were recorded with digitization rates in the 30-40 sample/second range. Thus, dynamic range permitting, these data provide potential resolution of seismic frequency content to 10 Hz and higher. For most of the Soviet PNE tests, these Borovoye recordings represent the highest quality regional seismic data which is available for detailed analysis.

The source characteristics of the 12 Soviet PNE tests selected for analysis are listed in Table 1 (Sultanov and Rubinshtein, 1995), where the events are listed in order of increasing epicentral distance from the Borovoye station. It can be seen from this table that these explosions encompass wide ranges of source medium (argillite, clay, dolomite, sandstone, limestone and salt), explosion yield (2.5 -23 kt) and source depth (593 - 2859 m). The associated distance range to Borovoye extends from 7.1 to 11.0 degrees, with two subgroups of six events each having average epicentral distances of about 8° and 10.5°, respectively. Given the distribution of the seismic networks being proposed to monitor the CTBT, this represents a very important distance range for investigation, which explains why these explosions were selected for the initial analysis. The map locations of these 12 explosions are shown in Figure 1, where it can be seen that both the 8° and 10.5° groups sample about 180° in azimuth with respect to the Borovoye station location. Thus, the Borovoye data recorded from these selected PNE events encompass a variety of different regional propagation path conditions, in addition to the previously noted range in source conditions.

Table 1: Source Characteristics of Selected Soviet PNE Events Recorded at the Borovoye Seismic Station

Date	Yield, kt	Depth, m	Source Medium	Epicentral Distance, Degrees
06/18/85	2.5	2859	Argillite	7.1
09/19/73	6.3	615	Argillite	7.6
10/04/79	21.0	837	Clay	7.7
10/26/73	10.0	2026	Dolomite	8.3
12/10/80	15.0	2485	Sandstone	8.8
08/25/84	8.5	726	Clay	8.9
04/19/87	3.2	2015	Limestone	10.4
08/15/73	6.3	600	Clay	10.5
10/03/87	8.5	1000	Salt	10.5
07/21/84	13.5	846	Salt	10.6
10/17/78	23.0	593	Sandstone	10.7
09/02/81	3.2	2088	Limestone	11.0

The broadband, vertical component data recorded at Borovoye from the six Soviet PNE events located at a common epicentral distance of about 8° are shown in Figure 2, where they are displayed in order of increasing azimuth as measured from Borovoye. In this display, the data are plotted as a function of apparent group velocity, which is useful for qualitative regional phase correlation since the epicentral distance is essentially constant for these events. The corresponding time scale for the average epicentral distance of 8° is indicated by the annotated interval shown at the bottom of this figure. It can be seen that these data exhibit some significant dependence on azimuth which is presumably related to propagation path differences. The most obvious difference is that the ratio of broadband amplitude in the 5 to 6 km/sec group velocity window (i.e., P_g) to that

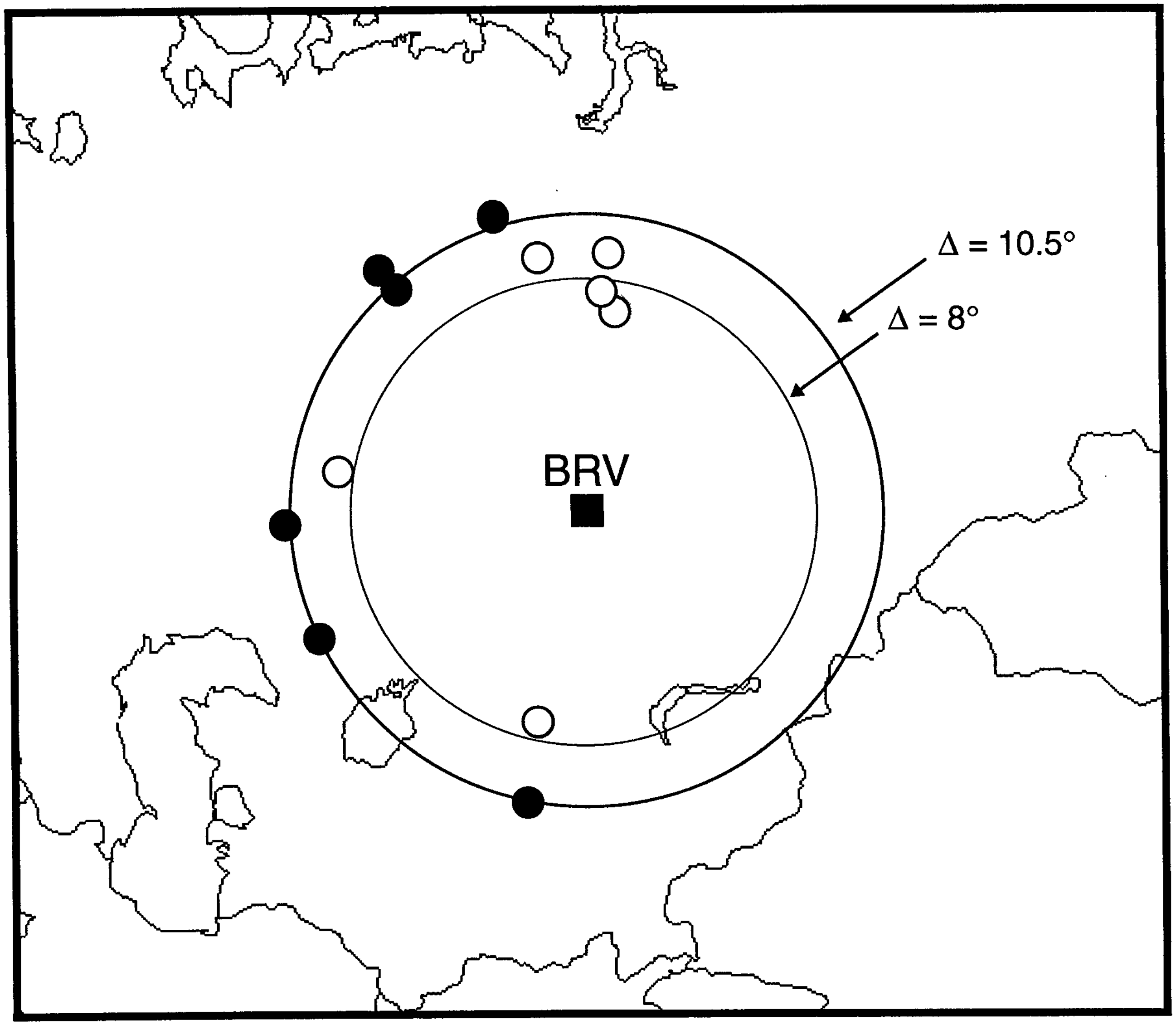

Figure 1. Locations of selected Soviet PNE events with respect to the Borovoye (BRV) station in North Kazakhstan. The open circles correspond to six explosions at an average epicentral distance of about 8 °; the filled circles correspond to six explosions at an average epicentral distance of about 10.5 °.

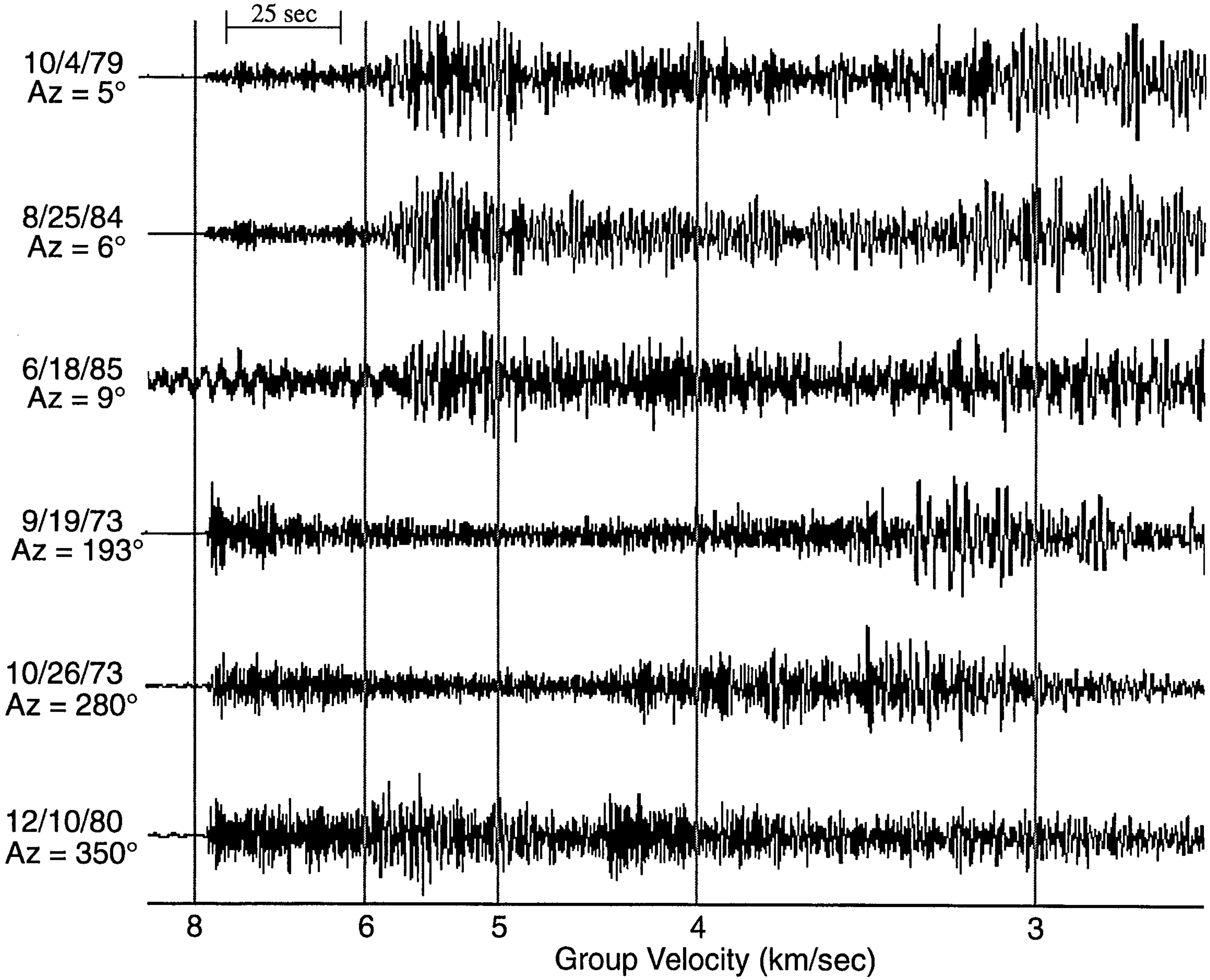

Figure 2. Vertical component regional signals recorded at Borovoye from six Soviet PNE events located at a common epicentral distance of about 8 °.

in the 6 to 8 km/sec group velocity window (i.e., P_n) is much larger for explosions located to the north of Borovoye than for those located south and west of the station. Moreover, if the 3 to 4 km/sec group velocity window is associated with L_g, it can be seen that the broadband L_g/P amplitude ratio varies from less than 1.0 (e.g., 12/10/80) to significantly greater than 1.0 (e.g., 10/26/73) for these explosions at an essentially constant distance from Borovoye. Thus, these data once again illustrate that propagation path variability can have a significant effect on the characteristics of the regional seismic signals observed from underground explosions.

The corresponding display of the data recorded at Borovoye from the six Soviet PNE events located at a common epicentral distance of about 10.5° is shown in Figure 3. Here again the data show significant variability as a function of azimuth, with the northernmost 10/17/78 explosion data showing an enhanced P_g/P_n ratio with respect to the observations at other azimuths consistent with that observed for the 8° data in Figure 2. A particularly notable recording in this distance range is that from the 9/02/81 explosion which shows evidence of large broadband S_n (i.e., 4 to 5 km/sec group velocity window) and L_g amplitude levels with respect to that of P, which is more typical of earthquakes than it is of explosion sources.

While displays of Figures 2 and 3 provide good visualizations of the variations in relative regional phase excitation levels between the different explosions, they do not illustrate the corresponding variations in absolute amplitude level. This information is represented in Figures 4 and 5 where the seismograms of Figures 2 and 3 have been approximately normalized for yield differences and replotted at the same absolute amplitude scale. For these purposes, the broadband amplitude levels were roughly normalized to a common average yield of 10 kt by assuming that they are directly proportional to yield. It can be seen that at both distance ranges, the normalized broadband signal amplitude levels vary quite considerably, but do not seem to show the same simple correlation with azimuth evidenced by the corresponding relative regional phase excitation levels. This presumably reflects the fact that the effects of varying propagation path characteristics on the amplitude levels are being modulated by the effects of variations in seismic source coupling efficiency between these explosions detonated at different scaled depths in different source

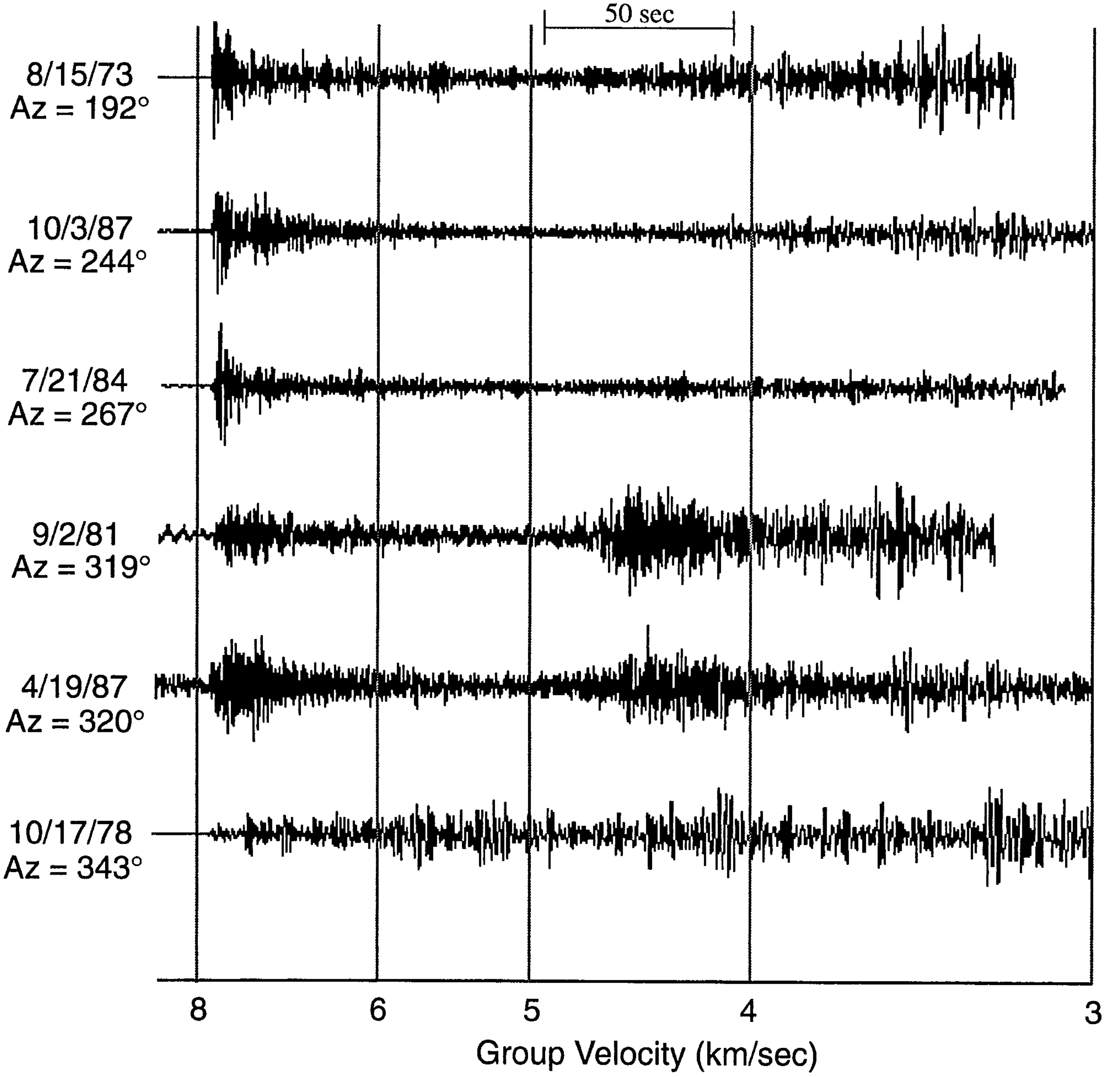

Figure 3. Vertical component regional signals recorded at Borovoye from six Soviet PNE events located at a common epicentral distance of about 10.5 °.

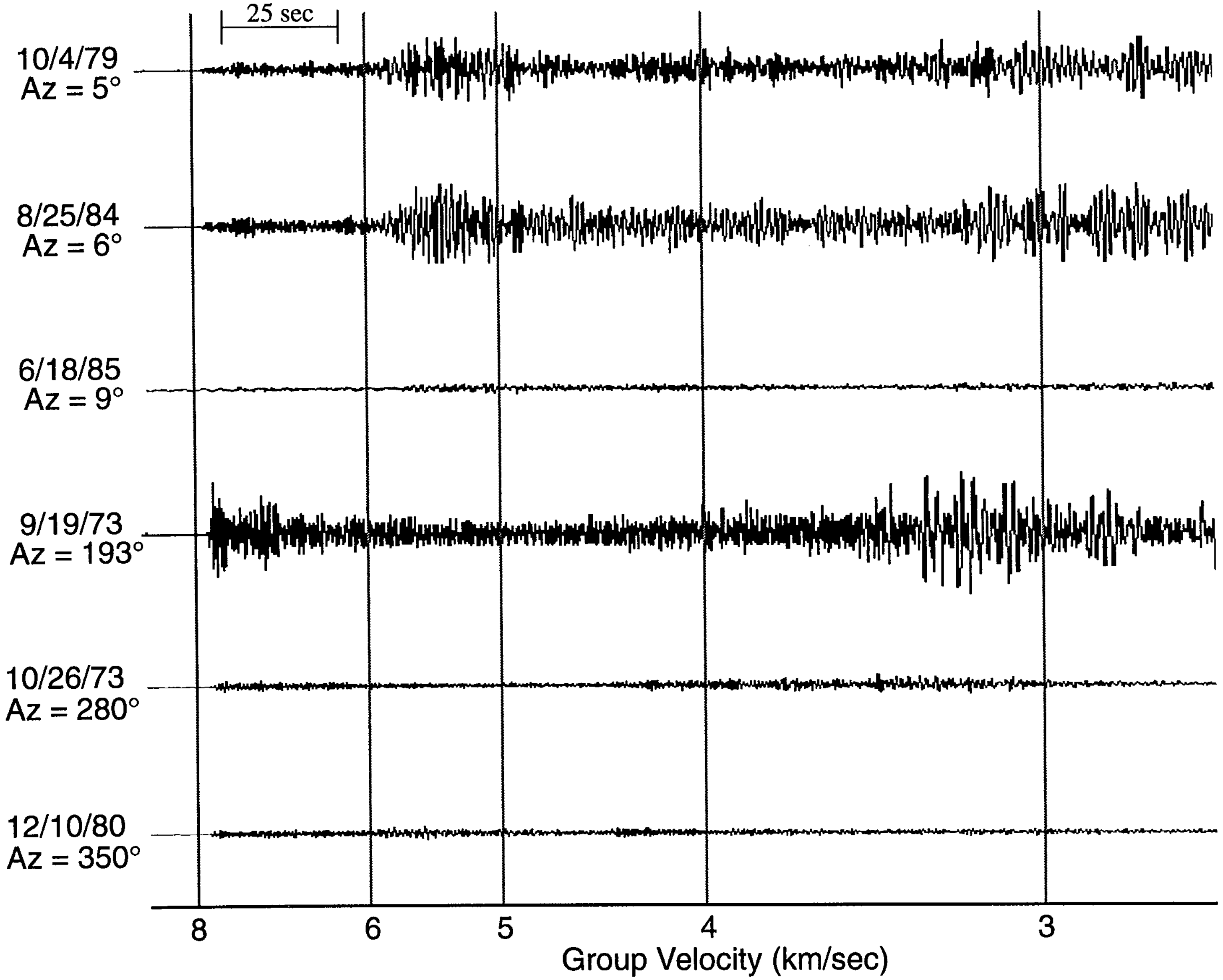

Figure 4. Vertical component regional signals recorded at Borovoye from six Soviet PNE events located at a common epicentral distance of about 8 °. Here the data have been approximately normalized to a common yield of 10 kt and plotted at a fixed absolute amplitude scale.

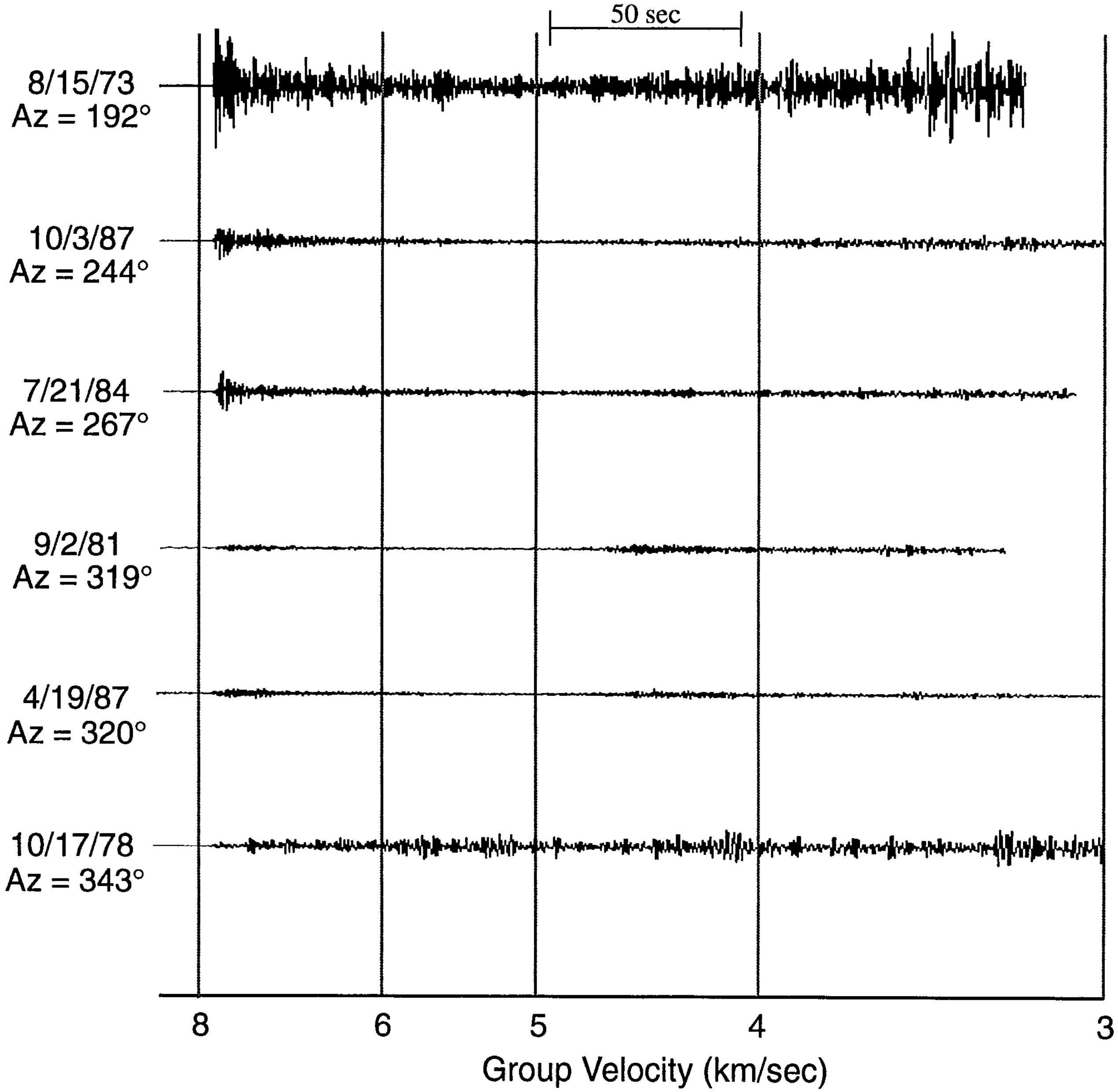

Figure 5. Vertical component regional signals recorded at Borovoye from six Soviet PNE events located at a common epicentral distance of about 10.5 °. Here the data have been approximately normalized to a common yield of 10 kt and plotted at a fixed absolute amplitude scale.

media. In any case, the selected data show a range of variability which must be considered as a lower bound to that which will have to be anticipated in global CTBT monitoring. Thus, they should provide some useful insights regarding the seismic detectability of evasively tested underground nuclear explosions.

3. SEISMIC DETECTION ANALYSIS

For a variety of historical and technical reasons, the seismic detectability of underground nuclear tests is generally expressed in terms of the teleseismic body wave magnitude value, m_b, which would be associated with a given test. However, this representation is somewhat ambiguous in that it is well-documented a given m_b value may correspond to a rather wide range of possible yield values depending on the explosive source conditions and the characteristics of the propagation paths from the source location to the stations of the monitoring network. These dependencies are schematically illustrated in Figure 6, where approximate m_b/yield curves corresponding to different testing conditions are compared. In this figure, the upper reference curve labeled "Good Coupling/Stable Region" corresponds to the m_b/yield relation

$$m_b = 4.45 + 0.75 \log W \tag{1}$$

which is associated with tamped explosions at nominal containment depths in hardrock at test locations in stable continental interior regions, such as the former Soviet Semipalatinsk test site (Murphy, 1993) in Central Asia. The corresponding "Good Coupling/Tectonic Region" curve shown in this figure was obtained from (1) by subtracting 0.40 units m_b to account for upper mantle attenuation bias such as that observed between NTS and Semipalatinsk. The curves labeled "Low Coupling" in this figure are meant to be representative of explosions in dry porous media such as the dry alluvium and tuff media at NTS and are offset below the corresponding reference hardrock curves by 0.75 units m_b. Finally, the curves labeled "Cavity Decoupled" are shown offset below the reference hardrock curves by 1.85 units m_b (i.e., the logarithm of the nominal full decoupling factor of 70). That is, it is assumed that the low frequency amplitude level of the seismic signal produced by a fully decoupled explosion at the same location as a fully tamped explosion of the same yield will be reduced by

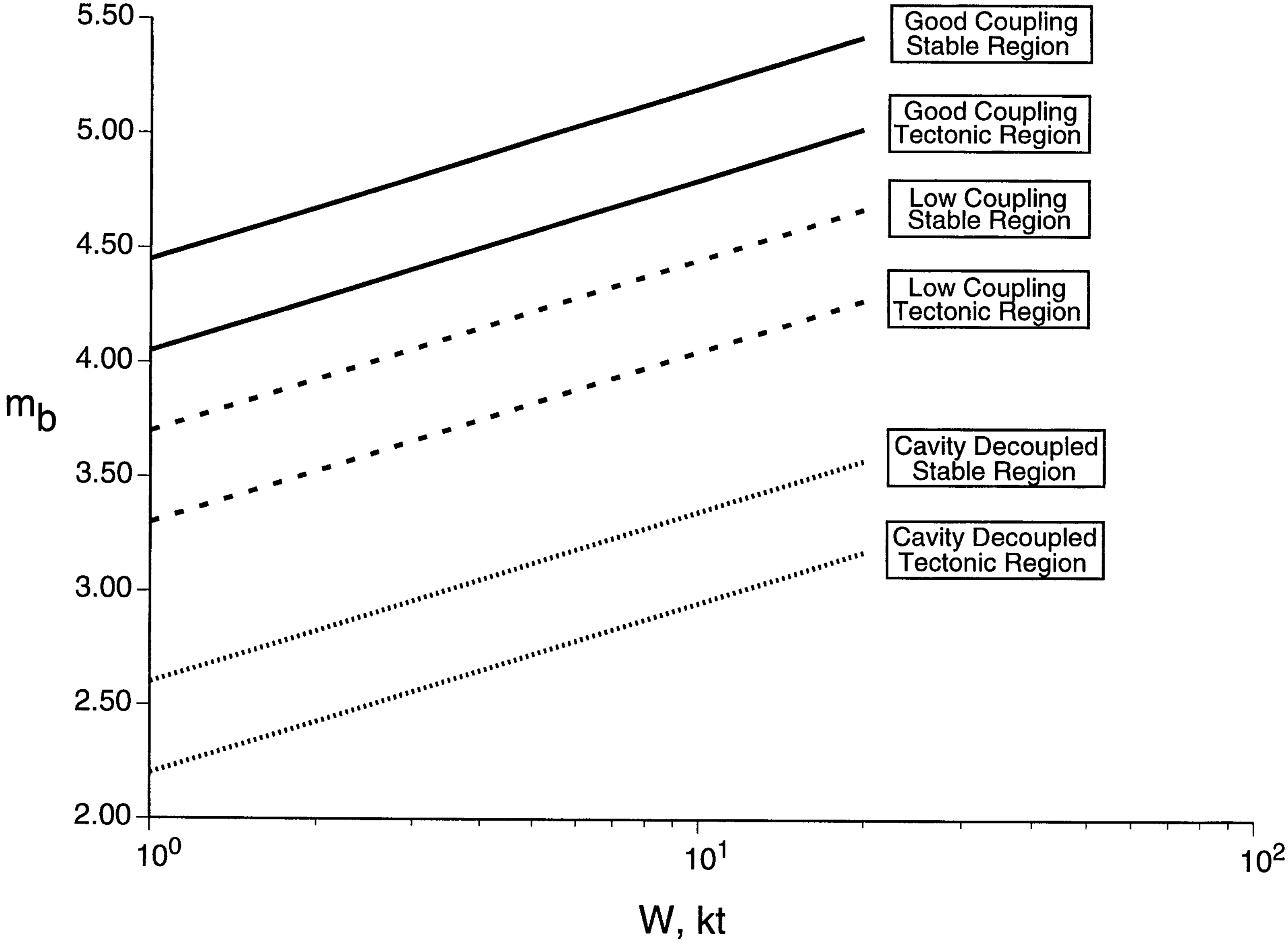

Figure 6. Comparison of m_b/yield relations for underground nuclear explosions illustrating the effects of test site tectonic environment and cavity decoupling.

a factor of 70, giving an m_b value 1.85 units lower than that associated with the tamped explosion. Similar reasoning applies in scaling to different yields. Thus, if a fully tamped explosion of yield $\tilde{W}$ has an associated body wave magnitude $\tilde{m}_b$ then, by simple source scaling for explosions at a fixed depth, a 1 kt tamped explosion at that same source location would be expected to produce a low frequency seismic amplitude level which is reduced by a factor of $\tilde{W}$ and to have an associated m_b value given by $\tilde{m}_b - \log(\tilde{W})$. It follows that a 1 kt fully decoupled explosion at that same source location would be expected to have an m_b value given by $\tilde{m}_b - \log(70\,\tilde{W})$. The corresponding algorithm for low coupling source media is somewhat different in that theoretical simulation results indicate that the low frequency full decoupling factor is significantly less than 70 for such media (Stevens *et al.*, 1991). In fact, these theoretical simulation results suggest that the m_b/yield curves for fully decoupled explosions in such low coupling media are quite similar to those shown for the hardrock media in Figure 6. In any case, it can be seen from Figure 6 that 1 kt fully decoupled nuclear tests at normal containment depths in stable and tectonic regions are expected to correspond on average to m_b values of 2.6 and 2.2, respectively. Similarly, 10 kt fully decoupled explosions in stable and tectonic regions are expected to correspond to m_b values of 3.35 and 2.95, respectively. Further variations of several tenths of a magnitude unit from these average values may be expected for cavity decoupled tests conducted in different media, or at depths significantly different from the nominal containment depths for tamped explosions with comparable yields (Murphy and Barker, 1994). Such source variability is explicitly included in the following analysis since the selected Soviet PNE events encompass wide ranges of source media and depth.

The scaling procedure used to derive the synthetic regional seismic data analyzed in this study has been described in detail in a number of previous reports (e.g., Murphy *et al.*, 1995). In this approximation, if the elastic radius of the source of the tamped reference explosion of yield W_T is denoted as rel_2, then the elastic radius for the corresponding cavity decoupled explosion is

$$\mathrm{rel1} = \frac{rel_2}{(DF)^{1/3}} \qquad (2)$$

where DF denotes the low frequency decoupling factor. Thus, assuming a nominal full decoupling factor of 70, the value of DF to be used in scaling to a 1 kt fully decoupled explosion is simply 70 W_T. In general, the source scaling operator is frequency dependent and acts as a high pass filter in applications of interest in the present study. This fact is illustrated in Figure 7 which shows the source spectral ratio required to scale a recording from a 1 kt explosion in hardrock to the corresponding estimate of a 1 kt fully decoupled recording. In this example, the scaling operator reduces the low frequency spectral amplitude level by the nominal factor of 70, while reducing the 10 Hz spectral amplitude level by only about a factor of 10. The detailed spectral shape of this decoupling operator depends to some extent on source medium and depth. For the 12 selected Soviet PNE tests of Table 1 recorded at Borovoye, the Mueller/Murphy granite source model (Mueller and Murphy, 1971) was used for all the source media except clay, in accordance with the previous analysis results of Murphy and Barker (1994). The lower source corner frequencies for explosions in clay were approximately modeled by reducing the source medium velocity in the Mueller/Murphy granite model from 5.5 km/sec to 3.5 km/sec, consistent with the results of the analysis of the seismic source function for explosions in clay described in that report.

The source scaling procedure is graphically illustrated in Figure 8 using the Borovoye data recorded from the 10 kt PNE event of 10/26/73 which was detonated at a depth of 2026 m in dolomite. This figure shows the observed broadband Borovoye recording of this explosion (top) together with the results of theoretically scaling it to correspond to 1 kt tamped and 1 kt fully decoupled explosions at that same source location. Note that in progressing from the observed to the simulated 1 kt decoupled recording, the L_g/P ratio decreases significantly, consistent with the frequency dependent nature of the source scaling illustrated in Figure 7. That is, because the dominant frequency of the L_g phase is lower than that of the P phase, the broadband L_g amplitude level is reduced more by the scaling procedure than is the P wave amplitude level.

All of the Borovoye recordings from the 12 Soviet PNE events of Table 1 have been theoretically scaled to simulate the corresponding signals expected from 1 kt cavity decoupled explosions at those same source locations using the procedures illustrated in Figure 8. These synthetic data, together with the

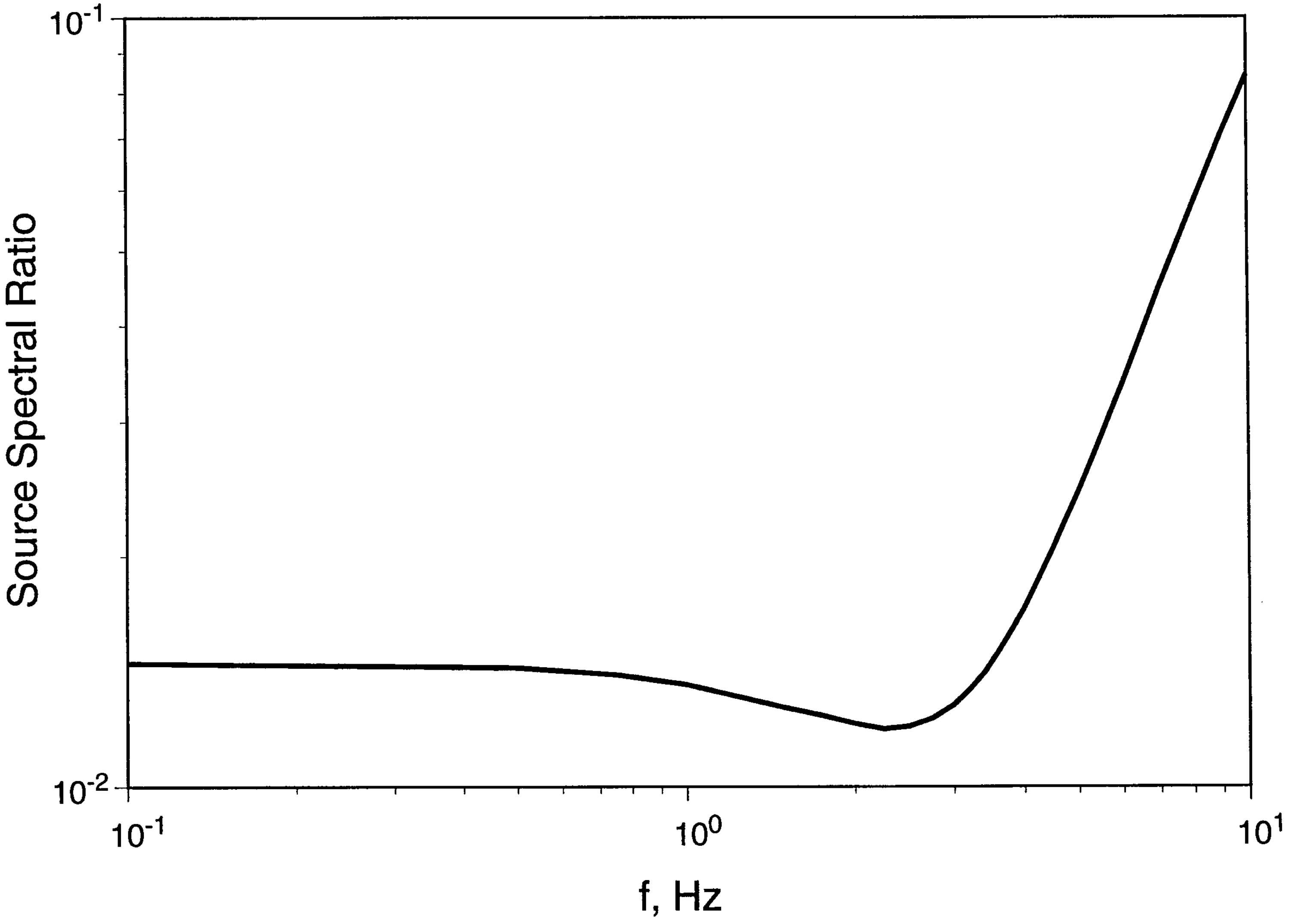

Figure 7. Theoretical seismic source spectral ratio of a 1 kt cavity decoupled explosion to a 1 kt tamped explosion in hardrock at normal containment depth.

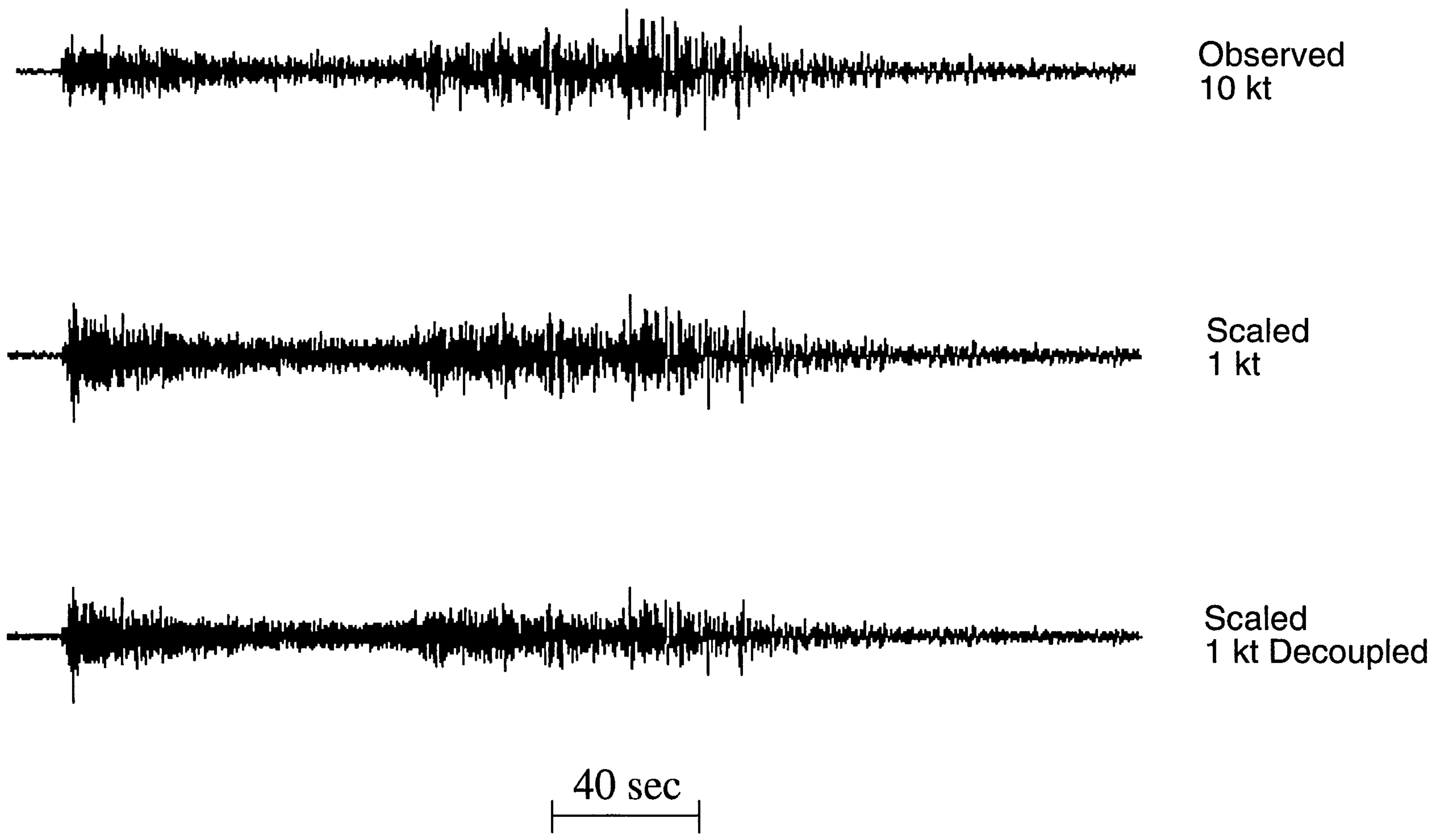

Figure 8. Comparison of observed and theoretically scaled broadband seismograms corresponding to the vertical component Borovoye recording of the Soviet PNE test of 10/26/73.

original pre-signal noise windows, were then bandpass filtered using a Gaussian comb of filters spaced at intervals of 0.25 Hz between 0.5 and 10 Hz, where each filter is characterized by a Q value of 6 f_c, with f_c the filter center frequency. The spectral amplitude levels at each center frequency were then estimated by computing the RMS values of the instrument-corrected filter outputs.

In order to assess the consistency of the Borovoye data and the associated calibrations, pre-signal spectral noise estimates were determined for each of the 12 selected PNE events of Table 1 and the results were averaged to obtain the Borovoye station frequency dependent noise estimate shown as a solid line in Figure 9. The dashed lines in this figure denote the $\pm 1\sigma$ levels about the mean which are associated with this sample of data. These σ values average to about a factor of 1.5 over this frequency band, which indicates that the background noise levels are quite stable at this site, and also suggest that the quoted system calibration factors must be quite accurate. Given the consistency of these results, the average noise as a function of frequency shown in figure 9 has been used in computing all the Borovoye signal/noise ratio estimates described in the following analysis.

The derived signal-to-noise ratio (S/N) estimates as a function of frequency at Borovoye corresponding to 1 kt fully decoupled nuclear explosions at the locations of the six events of Table 1 which are at an average epicentral distance of about 8° from Borovoye are summarized in Figure 10. In this figure, the solid line represents the logarithmic average of the individual S/N estimates as a function of frequency for these six PNE events and the dashed lines represent the associated upper and lower bounds on these S/N estimates. Note that the ratio of the upper to lower bound levels exceeds a factor of 10 over this entire frequency band, which reflects the large variations in regional seismic signal amplitudes associated with differences in source and propagation path characteristics between these six selected PNE events. It can be seen that the average S/N value at this distance is less than 0.1 for frequencies below about 4 Hz and increases only gradually with increasing frequency to a value of about 0.2 at 10 Hz. In fact, even the maximum S/N values for these six events are significantly less than 1 for frequencies below about 4 Hz and approach a maximum value of only about 1 at the highest frequencies analyzed. Thus, these results do not provide a very optimistic picture of the detectability of 1 kt fully decoupled explosions at an

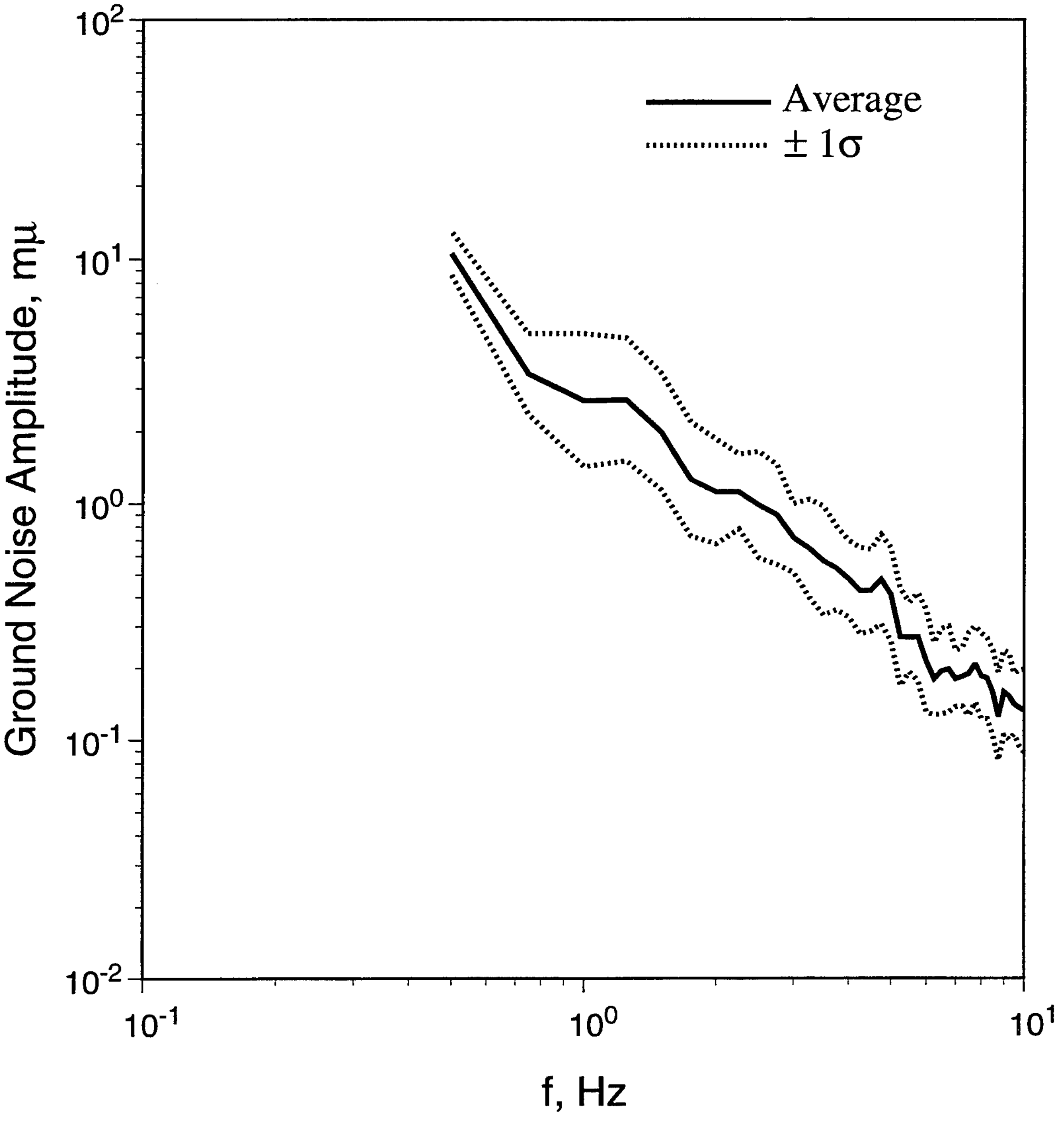

Figure 9. Noise levels as a function of frequency at the Borovoye station estimated from the pre-signal noise samples for the 12 selected Soviet PNE tests of Table 1.

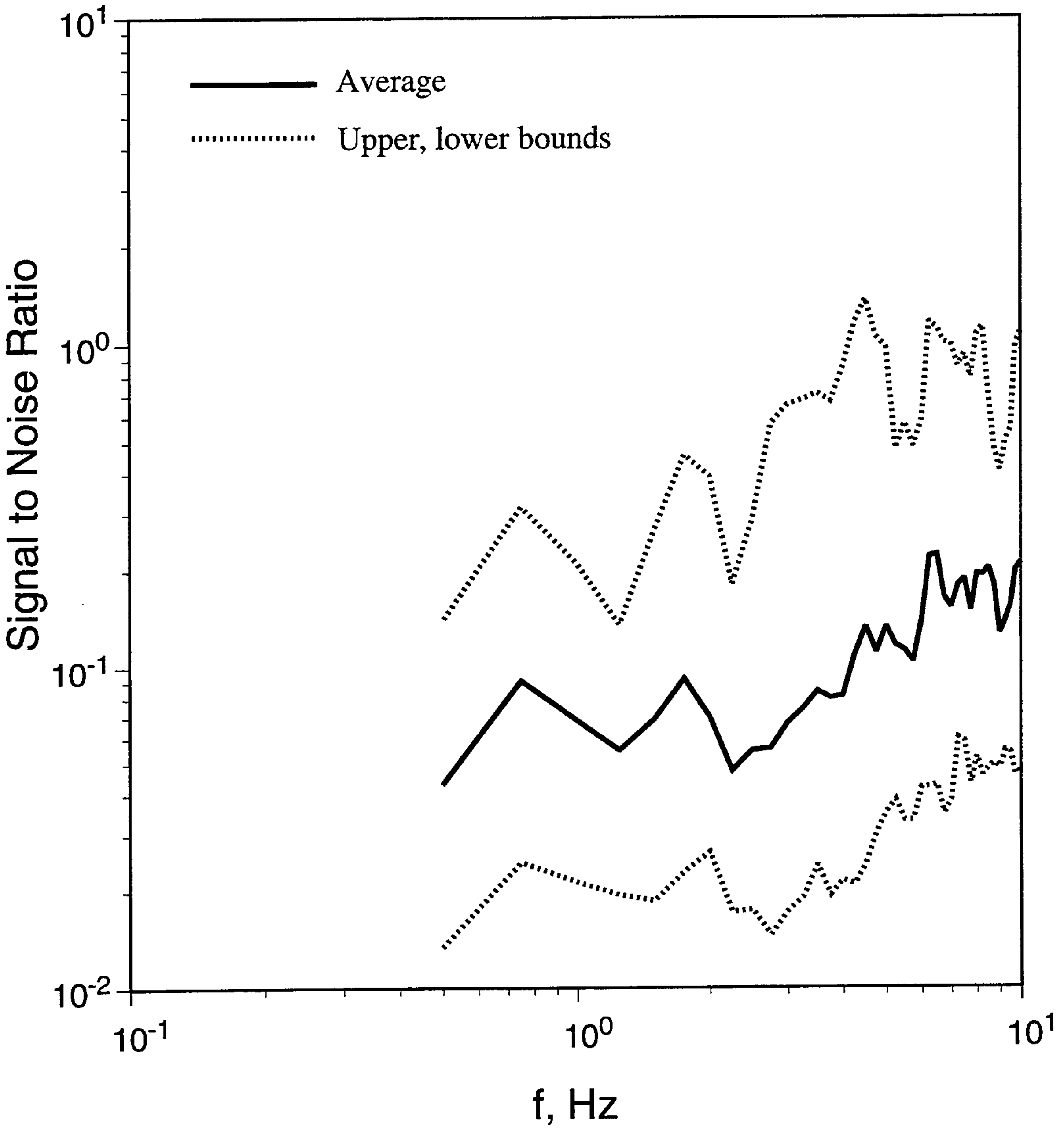

Figure 10. Estimated frequency dependent signal to noise ratios at the Borovoye station corresponding to six different simulated 1 kt cavity decoupled explosions at an average epicentral distance of 8° .

epicentral distance of 8° in Central Asia, at least for station noise conditions comparable to those shown in Figure 9.

The corresponding S/N results for 1 kt fully decoupled explosions at the locations of the six events of Table 1 which are at an average epicentral distance of about 10.5° from Borovoye are summarized in Figure 11. It can be seen that these results are very similar to those shown for the 8° distance events in Figure 10, with average S/N values of less than 0.1 for frequencies below about 4 Hz, and only very modest increase at higher frequencies. In this case, even the upper bound S/N values are less than 0.5 over the entire frequency band extending to 10 Hz, and show almost no increase with increasing frequency. This reduced frequency dependence with respect to the corresponding 8° distance values may be an indication that the high frequency anelastic attenuation effect is larger at this greater distance. In any case, the results for the two distance groupings are consistent to the extent that they indicate S/N values for 1 kt fully decoupled explosions recorded at the Borovoye station which are generally less than 1 over the entire short-period frequency band extending from 0.5 to 10 Hz. It remains now to assess the significance of these results in the context of other independent data and detection simulations.

The first issue to be addressed concerns the question as to whether the seismic signal levels observed from these selected PNE tests are representative of those observed in other regions under different source conditions. One partial answer to this question is provided in Figure 12, which shows a comparison of the simulated 1 kt decoupled peak amplitudes at 1 Hz at Borovoye for the 12 selected PNE events with the corresponding peak amplitude levels predicted by the Veith-Clawson (1972) $B(\Delta)$ curve. As is indicated on this figure, it was assumed for these prediction purposes that a fully tamped 1 kt nuclear explosion at normal containment depth in Central Asia is associated with an average m_b value of about 4.45, which implies a corresponding fully decoupled 1 kt average m_b value of about 2.60 (cf. Figure 6). It can be seen from this figure that the Veith-Clawson prediction is in reasonable agreement with the simulated peak amplitude values, although it is somewhat low on average, consistent with the fact that the Veith-Clawson $B(\Delta)$ curve at regional distances is based primarily on explosion data recorded in the Western U.S., where regional seismic wave propagation is relatively inefficient. Also shown on this figure is the Veith-

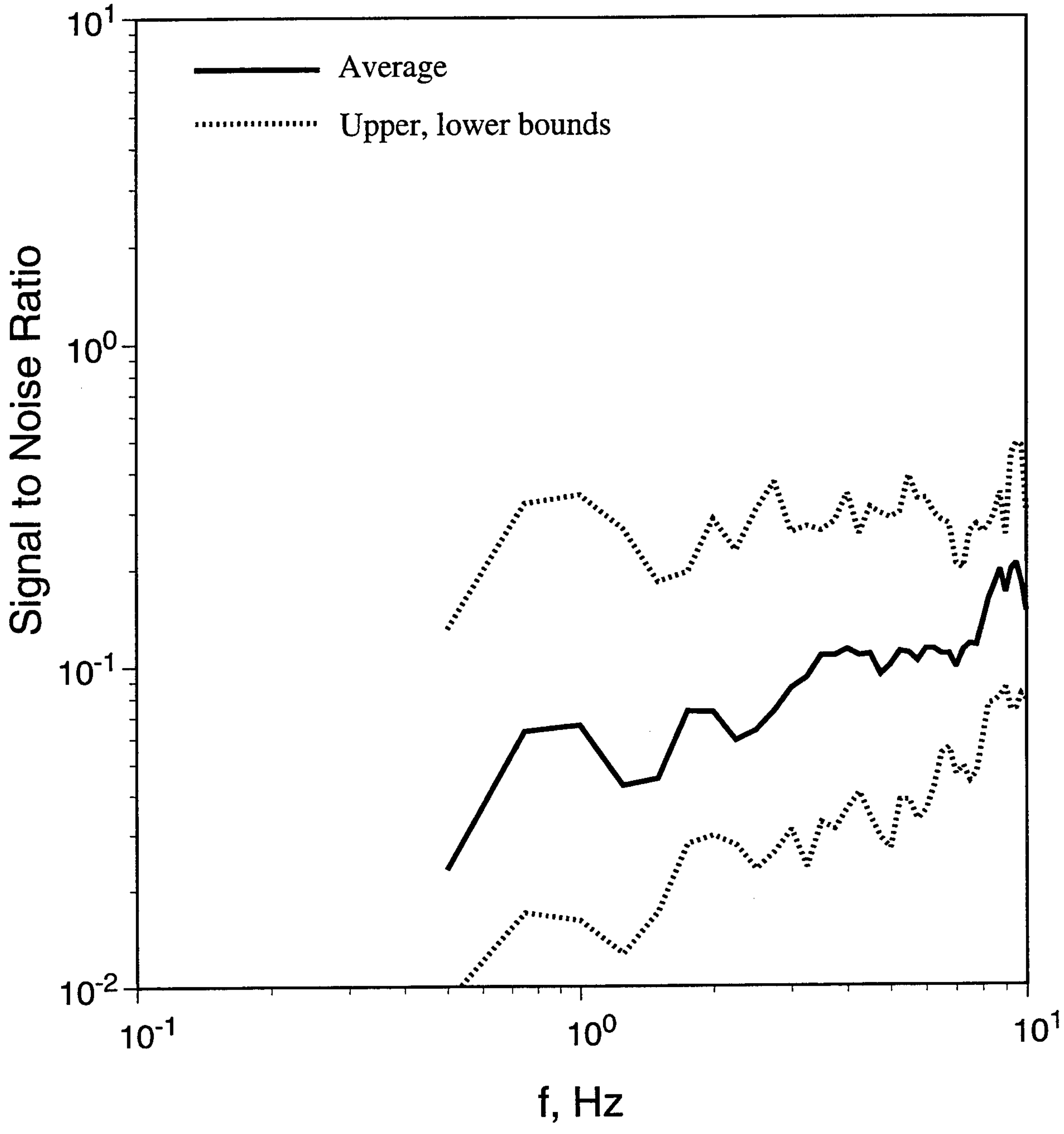

Figure 11. Estimated frequency dependent signal to noise ratios at the Borovoye station corresponding to six different simulated 1 kt cavity decoupled explosions at an average epicentral distance of 10.5° .

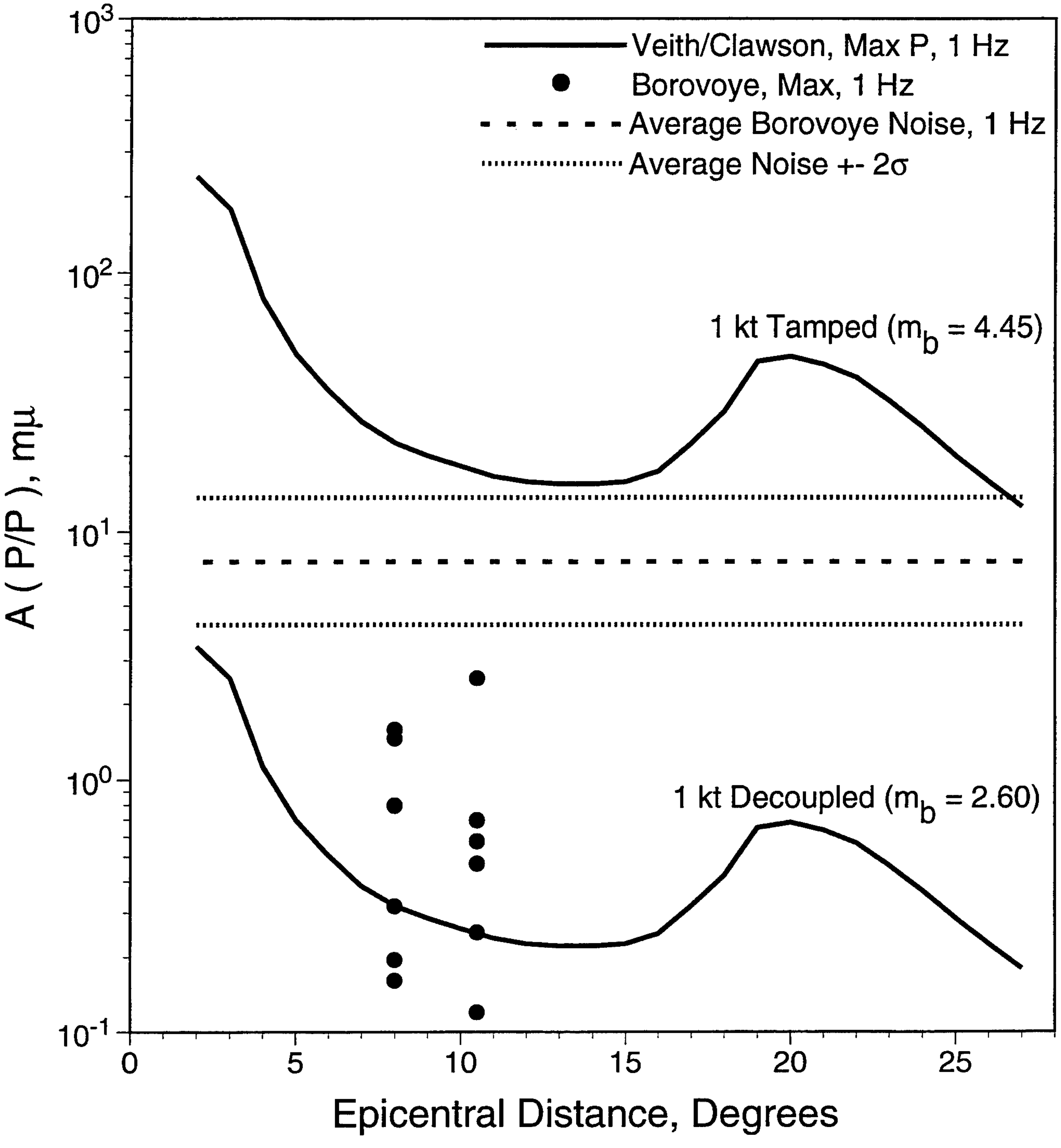

Figure 12. Comparison of the simulated 1 kt decoupled peak amplitudes at 1 Hz at Borovoye for the 12 selected PNE events with the corresponding peak amplitude levels predicted by the Veith-Clawson B(Δ) curve.

Clawson amplitude/distance prediction for a tamped 1 kt nuclear explosion in this location (i.e., $m_b = 4.45$), as well as the mean and $\pm 2\sigma$ bounds on the observed 1 Hz noise levels at Borovoye. It can be seen that these estimates indicate that a 1 kt tamped nuclear explosion in the distance range extending from about 8° to 10.5° from Borovoye should be detectable at 1 Hz, which is qualitatively consistent with the observed broadband signal-to-noise ratios for the lowest yield explosions of Figures 2 and 3. Note that the average peak-to-peak noise level at 1 Hz at Borovoye is about 7.5 mμ, which corresponds to an RMS value of about 2.5 mμ. Thus, Borovoye is a low noise station at 1 Hz, as has been noted previously by Adushkin and An (1990) and others.

Other evidence is provided by the Russian bulletin data reported for low yield Soviet PNE events. Figure 13 shows a plot of normalized peak amplitude data reported for the regional distance range extending from about 4° to 20° for 25 PNE events with yields in the 1.1 to 4.5 kt range. For the purposes of this analysis, the observed peak amplitudes were roughly normalized to an average yield of 3 kt by assuming that the amplitudes are directly proportional to yield. It can be seen that the scatter of these data is very large, reflecting the fact that the measurements were made at different frequencies on a variety of regional phases, as well as the inherent variability associated with differences in source conditions and propagation paths between these explosions. In any case, it can be seen that the average normalized amplitude level at a distance of 10° is about 60 mμ. Dividing by the yield (3 kt) and then the full decoupling factor of 70, this implies a 1 kt fully decoupled amplitude level of about 0.3 mμ at a distance of 10°, which is quite consistent with the simulated 1 Hz amplitude levels shown in Figure 12. A similar scaling analysis of the lower and upper bounds to the data of Figure 13 gives a range for the fully decoupled 1 kt amplitudes at 10° which extends from 0.05 to 2.0 mμ, which is very close to the range of the simulated values shown in Figure 12. Therefore, it is concluded that the simulated 1 kt fully decoupled Borovoye amplitude levels at 1 Hz, estimated from the 12 selected PNE events are generally consistent with other independent data sources for the region, at least within the rather large data scatter.

It is also of interest to assess how the results of the present study compare to previous analyses of the seismic detectability of low yield decoupled explosions. Bennett *et al.* (1995) recently published a study in which they

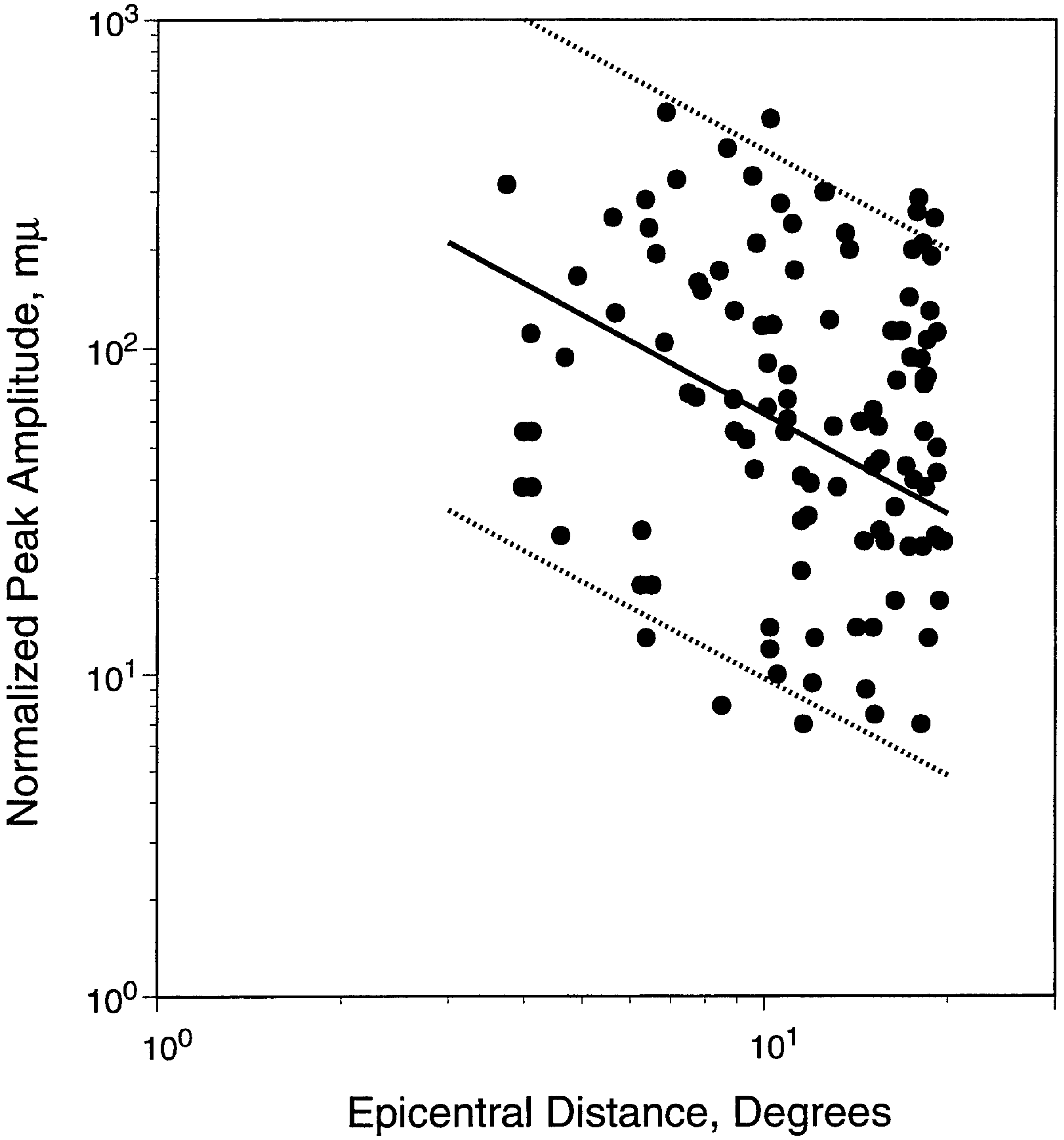

Figure 13. Normalized peak amplitude data versus distance for 25 low yield (W < 5kt) Soviet PNE events. These data were obtained from Russian seismic bulletins and have been approximately normalized to an average yield of 3kt by assuming that the amplitudes are directly proportional to yield.

theoretically scaled observed regional seismic signals recorded from tamped explosions at the former Soviet Novaya Zemlya and Semipalatinsk test sites and the Chinese Lop Nor test site to simulate those to be expected from 1 kt fully decoupled explosions at those same source locations. Their results were generally in agreement with those reported here in that they indicated that such low yield, evasively tested nuclear explosions would be difficult to detect at most of the regional stations which were analyzed. Notable exceptions to this general finding were the scaled Scandinavian ARCESS array recordings of Novaya Zemlya explosions. For this station at an epicentral distance of about 10°, it was found that a simulated 1 kt fully decoupled nuclear test at Novaya Zemlya should be clearly detectable at frequencies above about 3 Hz. This result is inconsistent with the corresponding PNE results of Figure 11, and it is therefore appropriate to examine this case in greater detail. Clearly, either the signal or noise levels at ARCESS must be quite different than those at Borovoye. Considering first the relative signal levels, the ARCESS signal level as a function of frequency derived from the theoretically scaled recording of the Novaya Zemlya tamped nuclear explosion of 10/24/90 is shown in Figure 14, where it is compared with the upper and lower signal bounds derived from the scaled Borovoye recordings of the six PNE events at an average epicentral distance of 10.5°. It can be seen that the estimated ARCESS signal level for this 1 kt fully decoupled scenario is very comparable to the corresponding average Borovoye signal levels below about 3 Hz, but that at higher frequencies the ARCESS signal level is somewhat larger. While this difference in signal spectral composition contributes somewhat to the enhanced detectability at ARCESS, it is only about a factor of 2 to 3 at high frequencies and this is not large enough to explain the observed differences in signal-to-noise ratio. Therefore, it is necessary to also evaluate the relative noise backgrounds at the two stations.

Estimates of the ARCESS and Borovoye background noise as a function of frequency are shown in Figure 15 where it can be seen that, although the Borovoye levels are lower for frequencies below about 1.5 Hz, the ARCESS noise levels drop off much more rapidly at higher frequencies and are lower than the Borovoye levels by about a full order of magnitude at 10 Hz. In fact, between 2 and 10 Hz the ARCESS noise amplitude spectrum decreases approximately as $f^{-2.25}$, while the Borovoye noise amplitude spectrum drops off with increasing frequency as $f^{-1.50}$. Thus, while Borovoye is a very low noise

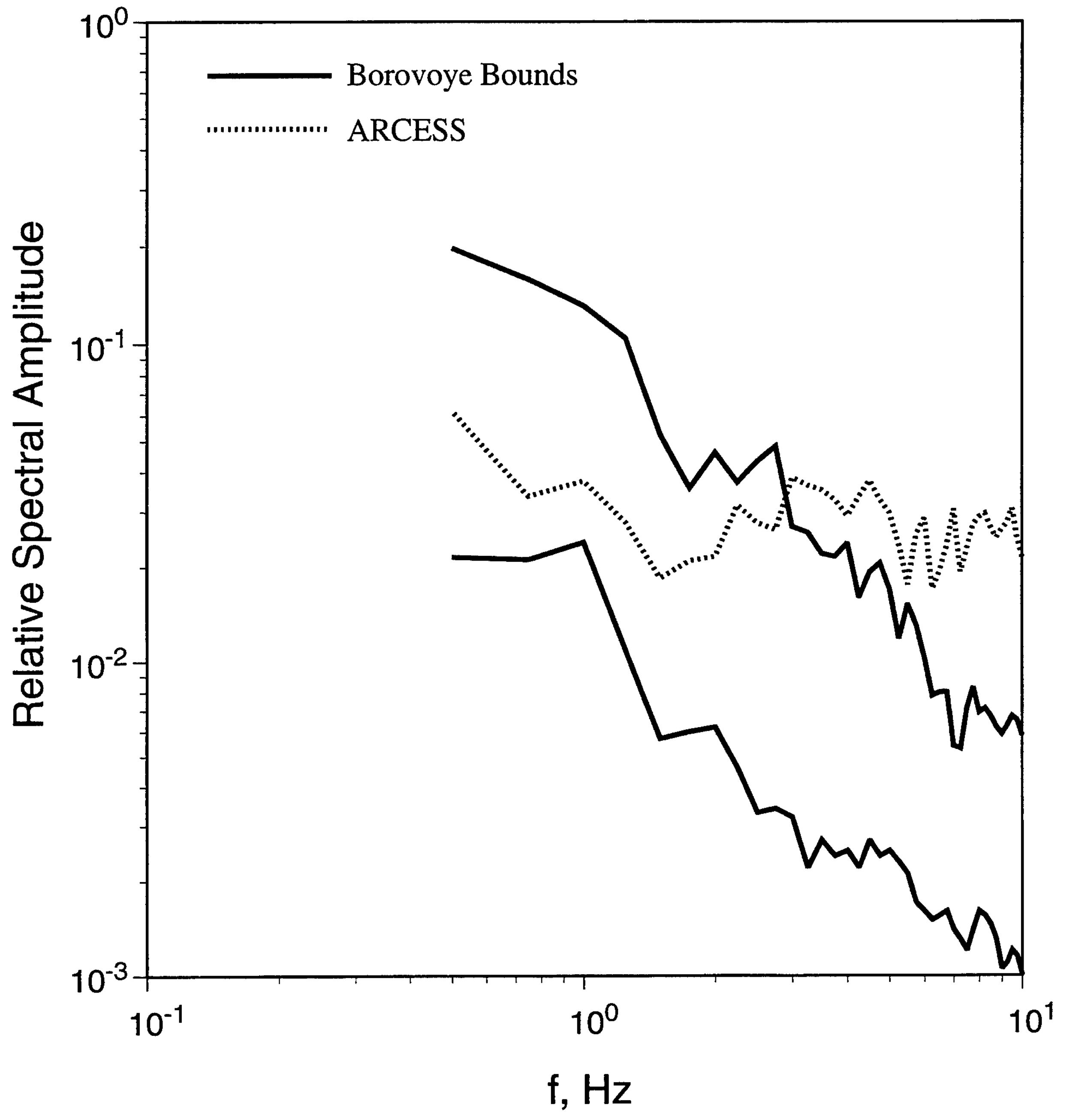

Figure 14. Comparison of ARCESS and Borovoye signal spectra estimates corresponding to 1 kt fully decoupled nuclear explosions.

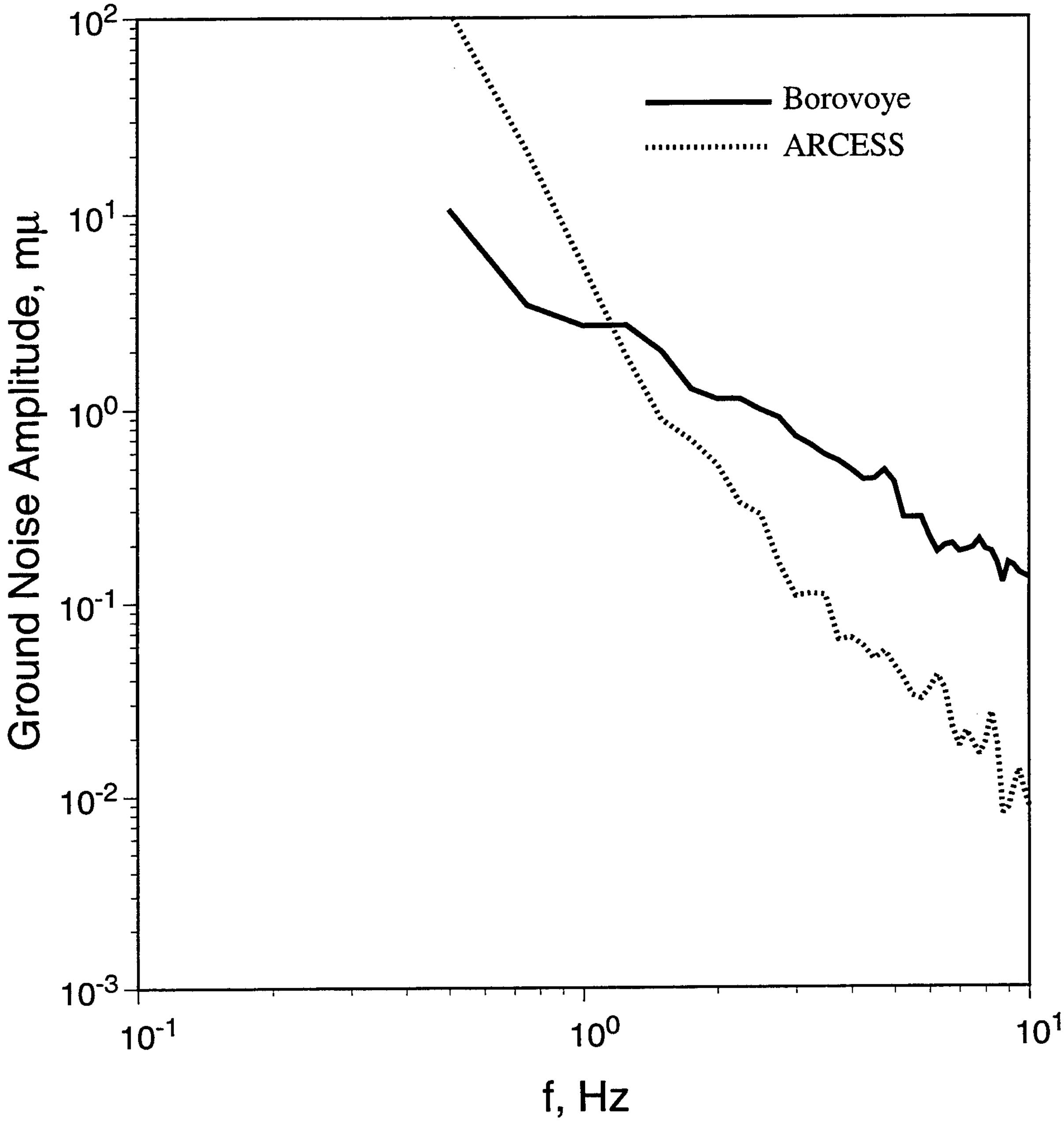

Figure 15. Comparison of Borovoye and ARCESS background noise spectra.

station at around 1 Hz, it is not low noise at high frequencies, at least with respect to ARCESS. It is not clear at this time whether this increased high frequency noise level at Borovoye is associated with system noise or with the ground noise characteristics at that station, but, in either case, it has a profound effect on estimates of seismic detectability. The average Borovoye/ARCESS noise spectral ratio computed from the spectra of Figure 15 is shown in Figure 16, together with a simple analytic approximation (dashed line) which provides a smoothed fit to the observed frequency dependent ratio. This analytic approximation will be used to represent the frequency dependent noise differences between the stations in the following discussions of seismic detectability.

The effects of differences in the background noise characteristics on seismic detectability at Borovoye are illustrated in Figures 17 and 18 where the average Borovoye S/N estimates from Figures 10 and 11 (solid lines) are compared with the corresponding S/N estimates which would be expected if the Borovoye background noise was comparable to that at ARCESS (dashed lines). As would be expected from the comparison of Figure 15, if the ARCESS noise conditions prevailed at Borovoye, the average estimates of seismic detectability would improve dramatically at both the 8° and 10.5° distance ranges, with both showing S/N values which are generally greater than 1 for frequencies above about 6 Hz. However, even in this case, the average S/N values in the 8-10 Hz band are only about 2, and such a narrowband signal would have to be considered marginal for detection and identification purposes.

In order to put the above comparison of different noise levels into a proper perspective, it is appropriate to consider how the Borovoye and ARCESS noise levels compare with the general reference standards which have been published in recent years. For example, Figure 19 shows a comparison of the Borovoye and ARCESS noise amplitude spectra with the nominal "low noise" and "high noise" spectral bounds proposed by Peterson (1993) which are often used in network modeling programs. It can be seen that the ARCESS estimate is near the lower bound at high frequencies and that the Borovoye is generally lower than average over the entire frequency band extending from 0.5 to 10 Hz. Thus, estimates of seismic detectabililty based on ARCESS data would seem to be among the best which can be expected, which helps to explain the wide variations in detectability between stations reported by Bennett *et al.* (1995).

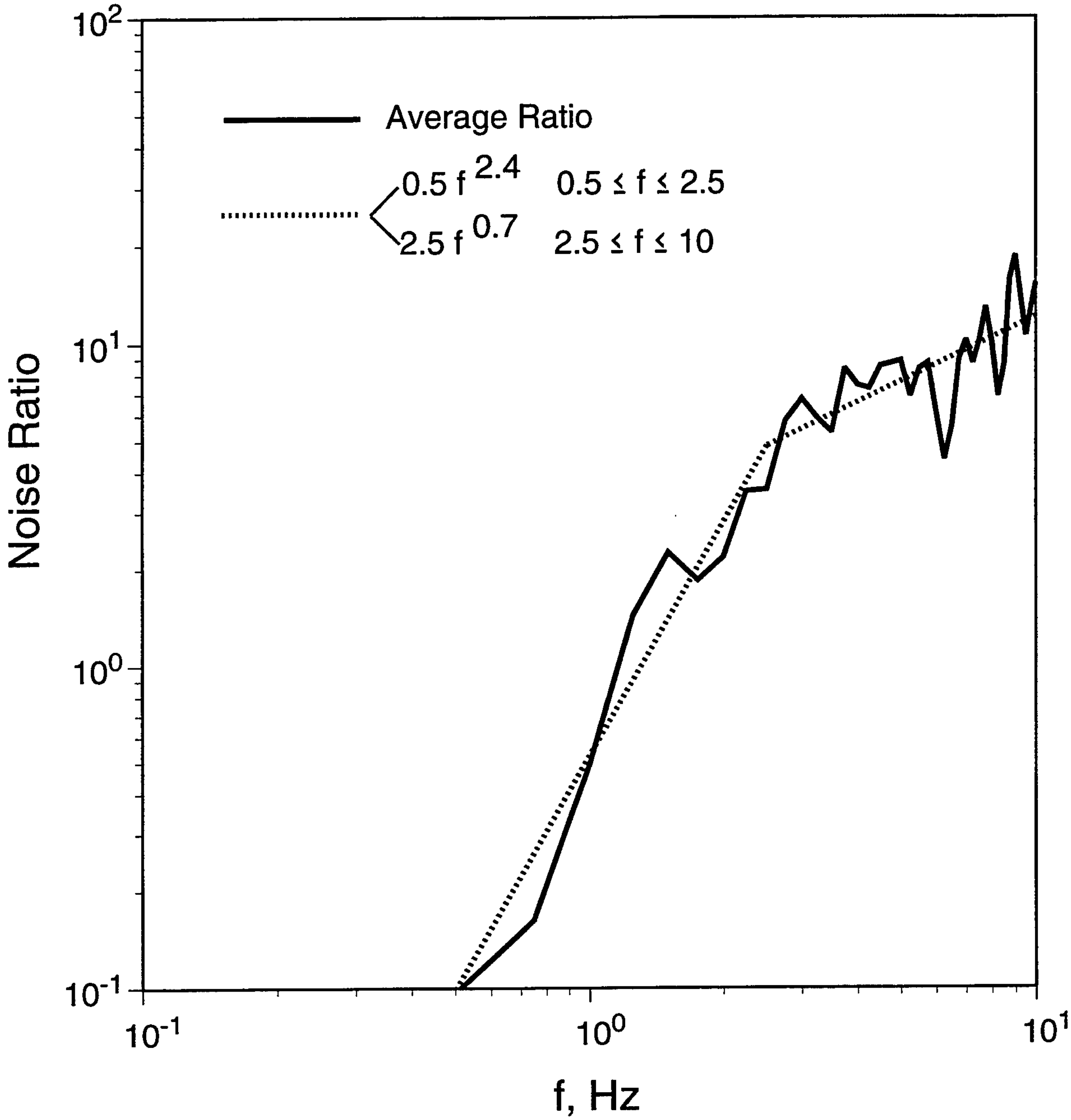

Figure 16. Ratio of average Borovoye to ARCESS background noise levels as a function of frequency.

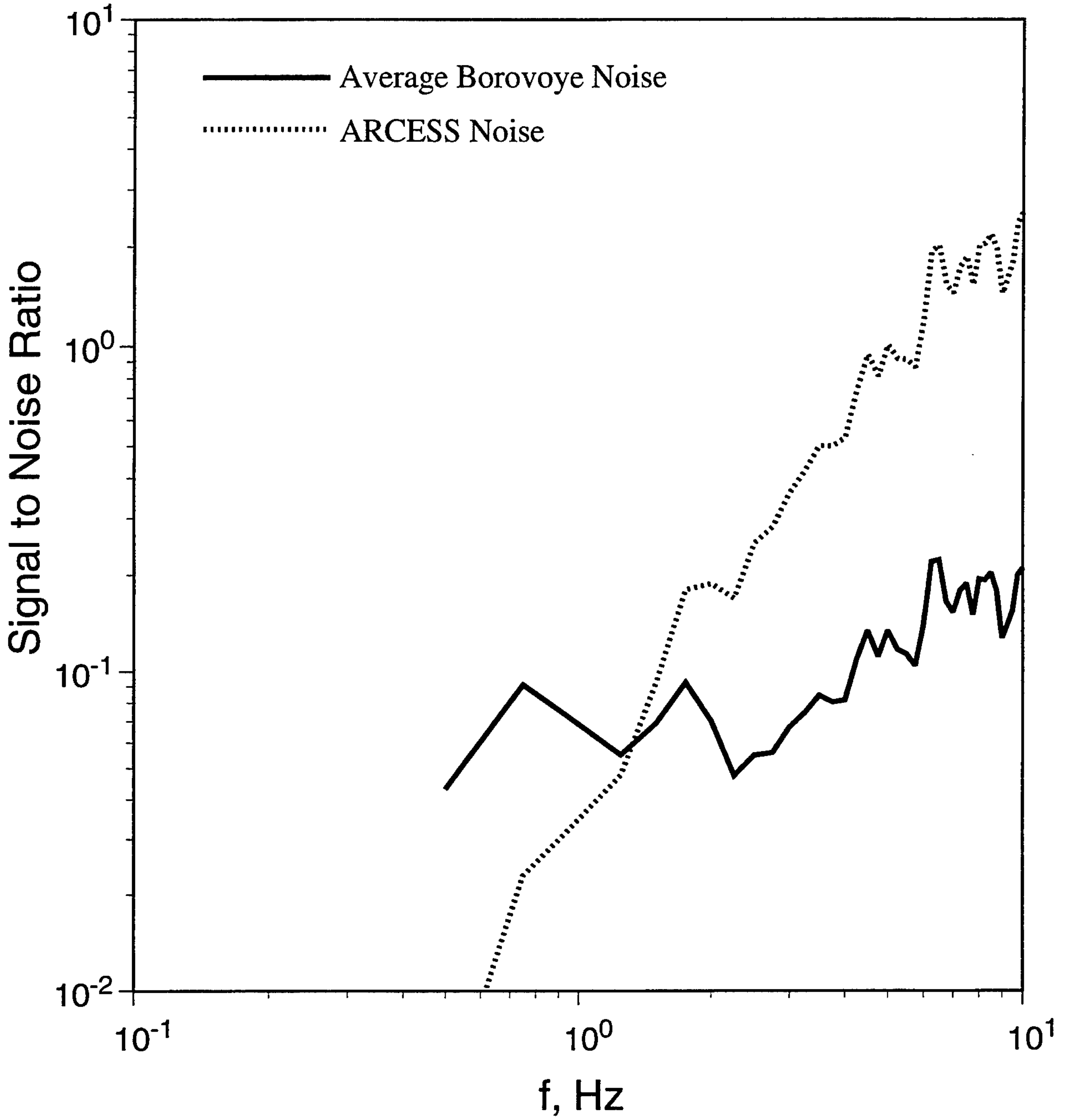

Figure 17. Comparison of the average Borovoye signal to noise estimate from Figure 10 (solid) with the corresponding estimate obtained using the ARCESS noise model (dashed). These estimates are for 1 kt fully decoupled nuclear explosions at an average distance of 8° from Borovoye.

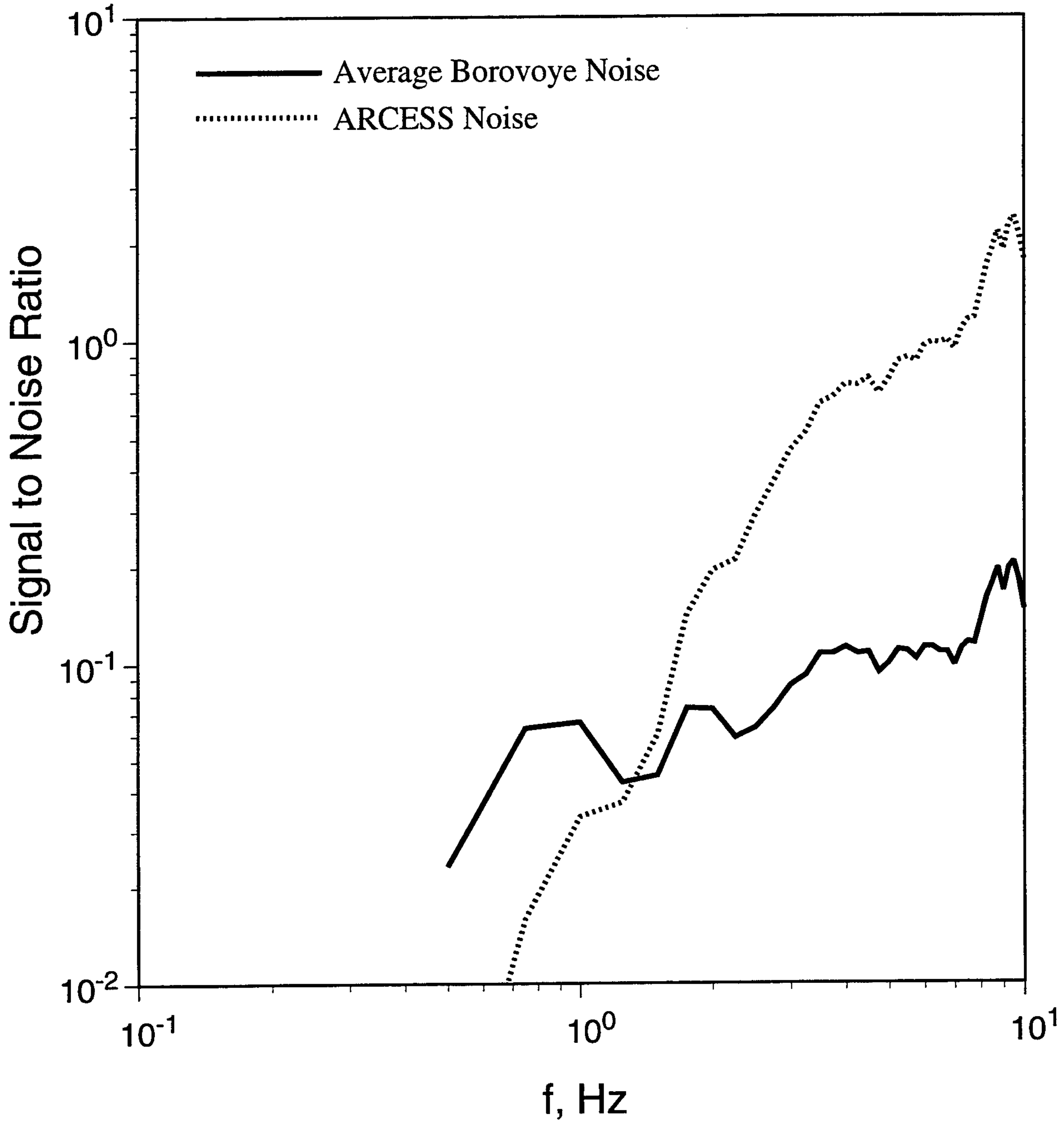

Figure 18. Comparison of the average Borovoye signal to noise estimate from Figure 11 (solid) with the corresponding estimate obtained using the ARCESS noise model (dashed). These estimates are for 1 kt fully decoupled nuclear explosions at an average distance of 10.5° from Borovoye.

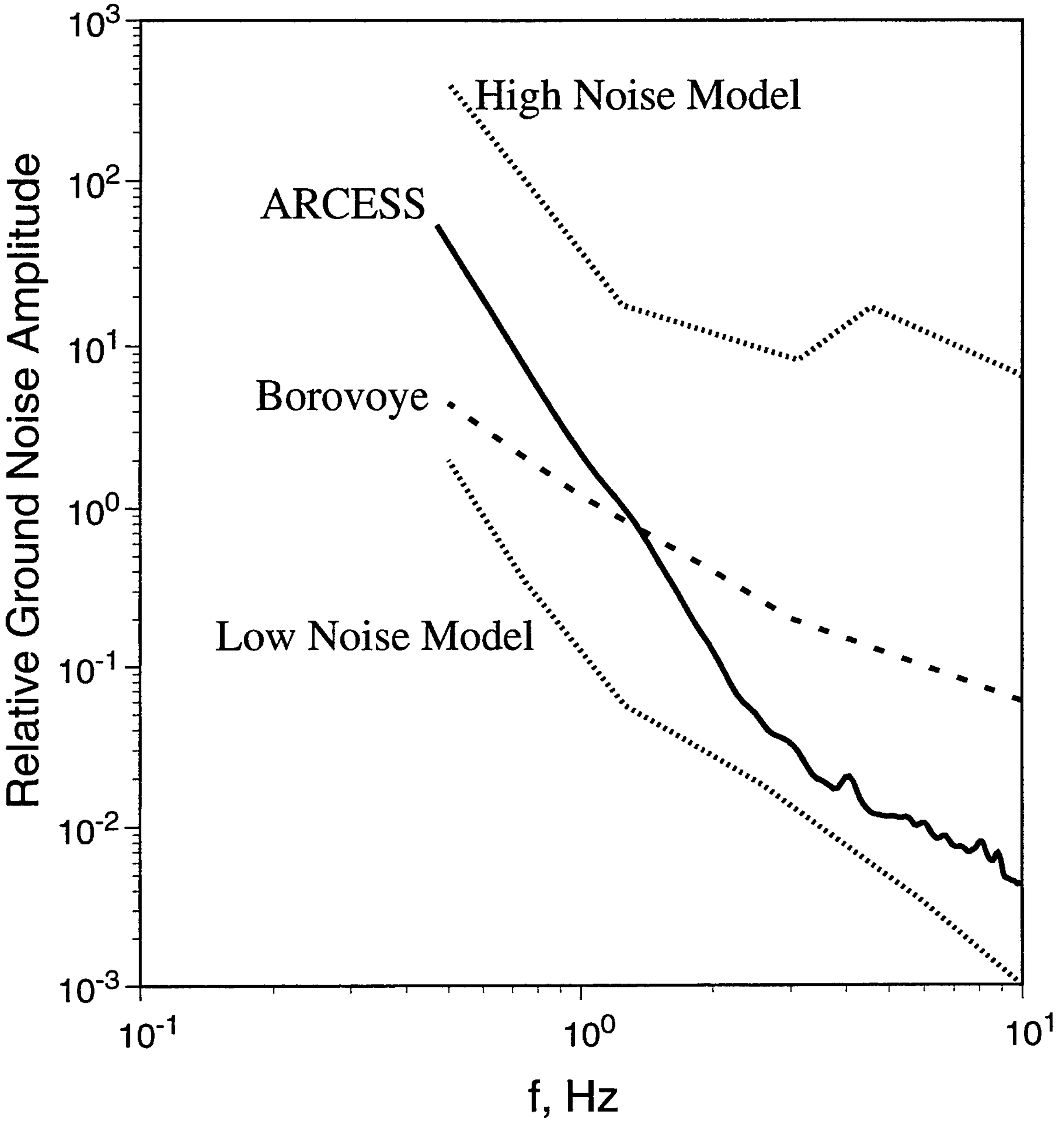

Figure 19. Comparison of Borovoye and ARCESS background noise estimates with the low and high noise models proposed by Peterson(1993).

Thus, the results of the present analysis are generally consistent with those of previous studies in that they indicate that the seismic detection of low-yield, cavity decoupled nuclear explosions will be difficult, even with high quality stations at regional distance of 10° or less. However, there are some potentially important caveats to this general conclusion which should be considered in assessing CTBT monitoring capability. For example, it should be noted that the simulation analyses presented in this report are based on single station data and do not account for any gain in S/N which might be achievable through signal processing of array data of the type that is routinely conducted at the ARPA regional arrays. On the other hand, there are some reasons to be cautious in attributing large improvements in detectability to such processing in the present application. In particular, since the S/N values which have been presented in this report are referenced to the maximum RMS signal amplitudes on the narrowband filter outputs and not to the amplitude of the initial P wave arrivals, they must be considered as upper bounds with respect to P, and this would tend to offset any potential gains associated with array processing. More fundamentally, the estimated S/N values for the 1 kt fully decoupled scenario described above are generally quite low in the frequency band below about 5 Hz where beamforming is most effective, and only approach the limits of detectability at higher frequencies, where signal processing gains are expected to be considerably smaller. In fact, many of the regional array processing systems being employed in the GSETT-3 prototype International Monitoring System do not even compute coherent beams for frequency bands above 5 Hz. Moreover, even if they become available, the monitoring utility of such narrowband detections is open to question. That is, since most of the regional seismic discriminants which have been shown to be promising (e.g., L_g/P spectral ratio, spectral scalloping) require relatively broadband data, it is not clear that narrowband detections will provide enough information to adequately characterize events in a verification context. It follows that some additional investigation will be required in order to insure that proposed seismic monitoring networks and associated signal processing systems are optimally designed to detect and identify any clandestine cavity decoupled nuclear explosions.

4. SUMMARY AND CONCLUSIONS

4.1 Summary

Seismic detection of small, evasively tested underground nuclear explosions remains as a major challenge to effective verification of any eventual CTBT. However, most seismic detection research reported to date has focused on analyses of regional seismic signals recorded from explosions at the few known nuclear weapons test sites and, consequently, represent only limited ranges of the source and propagation path conditions of potential monitoring interest. This report has provided a summary of the results of a joint research program under which scientists from S-CUBED have been working with scientists from the Russian Institute for Dynamics of the Geospheres (IDG) in an attempt to analyze a more representative sample of nuclear explosion data. In particular, regional seismic data recorded at the Borovoye Geophysical Observatory in Central Asia from selected Soviet PNE tests have been analyzed in order to characterize detectability over wider ranges of source and propagation path variables than those previously considered.

The characteristics of the selected Soviet PNE tests were described in Section 2, where the regional seismic data recorded at the Borovoye station from these explosions were also reviewed and analyzed. It was noted that the selected explosions encompass wide ranges in source medium (argillite, clay, dolomite, sandstone, limestone and salt), yield (2.5 - 23 kt) and source depth (593 - 2859 m) and, therefore, that they can provide valuable insight into the effects of explosion source conditions on seismic detectability. The regional seismic signals observed at the Borovoye station from these explosions were also examined and it was demonstrated that they show some significant and consistent dependence on source to station azimuth which illustrates the effects of propagation path variability on regional seismic signal characteristics.

The seismic detectability of low-yield, cavity decoupled nuclear explosions was addressed in Section 3, where data recorded at the Borovoye station from the selected PNE tests were theoretically scaled to simulate the corresponding seismic data which would be expected from fully decoupled explosions at those same source locations. The spectral compositions of these simulated seismic data were then estimated by processing them through a series of narrowband filters and the resulting signal spectra were compared with a variety of seismic background noise samples in order to estimate signal-to-noise ratios and associated probabilities of detection as a function of frequency over a band extending from 0.5 to 10 Hz.

4.2 Conclusions

The research summarized above supports the following principal conclusions regarding the seismic detectability of low-yield, cavity decoupled nuclear explosions:

(1) Variations in explosion source conditions and propagation path characteristics such as those considered in this study produce differences in regional seismic signal levels which can exceed an order of magnitude in the frequency band extending from 0.5 to 10 Hz.

(2) Analyses of simulated Borovoye seismic data corresponding to 1 kt fully decoupled nuclear explosions at the locations of the selected Soviet PNE tests in the epicentral distance range from 7.1 to 11 degrees indicate that such explosions would generally not be detectable at stations with background noise characteristics comparable to those at Borovoye.

(3) Borovoye is a very low noise station at frequencies of about 1 Hz and lower, but it is not a particularly low noise station at high frequencies.

(4) The seismic background noise levels at the Scandinavian ARCESS array station are more than an order of magnitude lower than those at Borovoye for frequencies approaching 10 Hz. However, even assuming such low background noise conditions, the estimated detectability of the simulated decoupled explosions at Borovoye is still marginal in most cases.

(5) The probability of seismic detection of low-yield, cavity decoupled explosions at regional distances is highest in frequency bands which lie above those normally employed for detection and identification analyses. Additional research is needed to optimize the seismic networks and signal processing procedures which will be required to adequately monitor such clandestine nuclear tests.

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