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The Stability of RMS Lg Measurements, and Their  
Potential for Accurate Estimation of the Yields  
of Soviet Underground Nuclear Explosions

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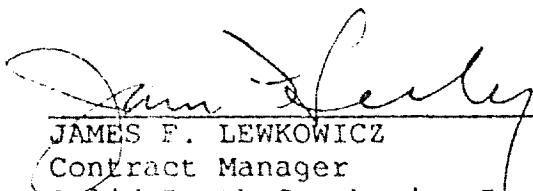
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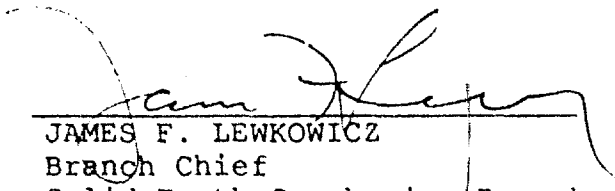
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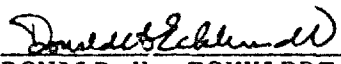
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Nuttli (1986) and Patton (1988) for Lg versus yield at Nevada, ~~this indicates that~~ RMS has a potential for yield estimation with very high accuracy at Shagan River.

*The* Our study has shown that: a) selected stations in the U.S.S.R. and China, situated at regional distances, provide a much improved signal-to-noise ratio of the Lg phase for events at Shagan River, as compared to NORSAR array data; b) the scaling of RMS Lg amplitudes between different sized events recorded at the same single station site appears to be consistent with that of NORSAR, indicating a remarkable degree of precision in single station measurements of Lg signal; c) RMS Lg amplitude measurements for the best of these stations may be made at 1.5 to 2.0 magnitude units lower than at NORSAR or Graefenberg, allowing a much lower threshold for Lg based yield determination; and d) the P-wave detection capabilities of these single stations do not match those of the NORESS and ARCESS arrays, thus teleseismic signals continue to be important for detection of small nuclear explosions.

Our conclusion is that Lg signals appear to provide an excellent basis for supplying estimates of the yields of nuclear explosions even down to below one kiloton, when such signals are recorded at high-quality digital in-country seismic stations, and when calibrated by access to independent (non-seismic) yield information for a few nuclear explosions at the test sites of interest. In the context of monitoring a low yield threshold test ban treaty, it will, in addition, be important to take into consideration various environmental conditions in the testing area, such as the possible presence of cavities, and to devise appropriate procedures for on-site observations in this regard.

## Preface

Under Contract No. F49620-C-89-0038, NTNF/NORSAR is conducting research within a wide range of subjects relevant to seismic monitoring. The emphasis of the research program is on developing and assessing methods for processing of data recorded by networks of small-aperture arrays and 3-component stations, for events both at regional and teleseismic distances. In addition, more general seismological research topics are addressed.

Each quarterly technical report under this contract presents one or several separate investigations addressing specific problems within the scope of the statement of work. Summaries of the research efforts within the program as a whole are given in annual technical reports.

This Scientific Report No. 4 presents a manuscript entitled "The stability of RMS Lg Measurements, and their potential for accurate estimation of the yields of Soviet underground nuclear explosions", by Roger A. Hansen, Frode Ringdal and Paul G. Richards.

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# THE STABILITY OF RMS Lg MEASUREMENTS, AND THEIR POTENTIAL FOR ACCURATE ESTIMATION OF THE YIELDS OF SOVIET UNDERGROUND NUCLEAR EXPLOSIONS

by

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## ABSTRACT

Data on underground nuclear explosions have recently become available from modern digital seismic stations installed within the Soviet Union and China. Observations of root mean square (RMS) Lg-wave signals for Soviet underground nuclear explosions at the Shagan River test site in East Kazakhstan show that the relative amplitudes of the RMS signals, at stations in Norway, the U.S.S.R., and China, are very similar for different explosions, the standard deviation of the differences being only about 0.03 in logarithmic units (i.e., magnitude units).

This is consistent with earlier observations comparing NORSAR and Graefenberg array data, and the observed scatter is significantly lower than has been reported for Lg data from Nevada Test Site explosions. In view of the excellent correspondence found by Nuttli (1986) and Patton (1988) for Lg versus yield at Nevada, this indicates that RMS Lg has a potential for yield estimation with very high accuracy at Shagan River.

Our study has shown that: a) selected stations in the U.S.S.R. and China, situated at regional distances, provide a much improved signal-to-noise ratio of the Lg phase for events at Shagan River, as compared to NORSAR array data; b) the scaling of RMS Lg amplitudes between different sized events recorded at the same single station site appears to be consistent with that of NORSAR, indicating a remarkable degree of precision in single station measurements of Lg signal; c) RMS Lg amplitude measurements for the best of these stations may be made at 1.5 to 2.0 magnitude units lower than at NORSAR or Graefenberg, allowing a much lower threshold for Lg based yield determination; and d) the P-wave detection capabilities of these single stations do not match those of the NORESS and ARCESS arrays, thus teleseismic signals continue to be important for detection of small nuclear explosions.

Our conclusion is that Lg signals appear to provide an excellent basis for supplying estimates of the yields of nuclear explosions even down to below one kiloton, when such signals are recorded at high-quality digital in-country seismic stations, and when calibrated by access to independent (non-seismic) yield information for a few nuclear explosions at the test sites of interest. In the context of monitoring

a low yield threshold test ban treaty, it will, in addition, be important to take into consideration various environmental conditions in the testing area, such as the possible presence of cavities, and to devise appropriate procedures for on-site observations in this regard.

## INTRODUCTION

We report our observations of root mean square (RMS) Lg-wave signals for Soviet underground nuclear explosions at the Shagan River test site in East Kazakhstan. We show that the relative amplitudes of the RMS signals, at stations in Norway, the U.S.S.R., and China, are very similar for different explosions. Thus, if we consider only well-recorded explosions (i.e. requiring that RMS Lg be at least 1.5 times the RMS level of noise preceding the P arrival), our basic observation is that RMS Lg amplitudes at pairs of stations are in excellent agreement, the standard deviation of the differences being only about 0.03 in logarithmic units (i.e. magnitude units).

This observation indicates that a seismic measure of source size can be estimated with unprecedented precision, from observations of Lg waves at a single station. (P-wave amplitudes, for example, as measured to obtain  $m_b$ , show significantly greater scatter.) We refer to such indications of precision of RMS Lg as "stability."

Quantitative studies of Lg began much later in seismology than such studies of P, S, and teleseismic surface waves, because Lg waveforms are in general more complex than those of other phases -- and Lg waveform modeling typically does not yet achieve the quality of fit between synthetics and data that has been attained with more conventional phases. It is therefore somewhat surprising to find that potentially the most precise estimator of seismic source size may be one based on a phase as complex as Lg.

In this paper, we are principally concerned with developing those properties of RMS Lg that are pertinent to making accurate estimates of the yield of Soviet nuclear explosions, particularly at the Shagan River test site. For Shagan River explosions with  $m_b > 5.5$ , Lg signals at NORSAR alone were found to provide magnitude estimates that indicated stability comparable to and possibly better than those obtained from P waves recorded on a large world-wide network (Ringdal, 1983). Underlying this conclusion are the assumptions, articulated by Nuttli (1973), that the magnitude of seismic sources can usefully be assigned at "long period" or "short period," and that short-period magnitudes can be estimated either with P waves, or, in many circumstances, with Lg recorded at periods around 1 s. We use  $m_b$  to denote short-period magnitude in general, and  $m_b(P)$  or  $m_b(Lg)$  where it is necessary to indicate the wave type used for measurement.

We report the first analyses of RMS Lg signals of Soviet nuclear explosions recorded within the U.S.S.R. We used data recorded at four in-country stations installed in the summer of 1988 by the Incorporated Research Institutions for Seismology (IRIS), under an agreement negotiated with the Soviet Academy of

Sciences. What is important about these stations, is that they have been allowed to run even during times when the Soviets were conducting underground nuclear explosions at weapons test sites, and for the first time this in-country data has routinely become available for analysis in the West. Using these four high-quality digital stations installed within the Soviet Union by IRIS and one installed by the British (GAM, The BSVRP Working Group, (1989)) located near the IRIS Garm station, we confirm that the stability of RMS Lg, observed teleseismically, is present at distances about 1500-3000 km from Shagan River, and can be used for explosions much smaller than those observed teleseismically. Specifically, we show an example for one of these IRIS stations, ARU (installed in 1988 at Arti in the Urals), indicating that the improvement in signal-to-noise ratio is such as to permit RMS Lg to be used for yield estimation of explosions down to about  $m_b$  4.0. We note that according to the magnitude-yield relations presented by Vergino (1989a),  $m_b$  4.0 would correspond to a yield well below one kiloton for nuclear explosions conducted under typical tamped conditions.

We further analyze RMS Lg signals from Shagan River explosions recorded at two stations of the China Digital Seismograph Network (CDSN). These stations, which have sampling rates of 20 Hz and operate in a triggered mode, are at Urumqi (WMQ) and Hailar(HAI), at a distance of 950 and 2900 km respectively from Shagan River. Stability of RMS Lg is again confirmed, and it appears that WMQ, if set to record continuously, could provide RMS Lg for yield estimation down to  $m_b$  3.5.

As part of this project to investigate Lg, we also address the excellent P-wave detection capability of the NORESS and ARCESS arrays (See Ringdal, 1990). We point out the advantages of combining the excellent *detection* capability of these teleseismic arrays with the potentially superior *yield-estimation* capability of in-country stations, for purposes of both detecting and estimating the yields of small nuclear explosions.

To place our new results in context, the next section reviews earlier studies describing the promise and the problems of using Lg signals. This review is followed by a description of our analysis of the Soviet and Chinese data.

## REVIEW OF PREVIOUS STUDIES OF LG

Lg waves are seismic waves that are observed to propagate across continental paths. They were first described by Press and Ewing (1952) from earthquakes in California which were observed at Palisades, New York, shortly after seismographs were installed at what then was called the Lamont Geological Observatory. The following characteristics were noted, for what these authors called "surface shear waves":

- (1) initial period about 0.5 to 6 seconds;
- (2) sharp commencements;



- (3) amplitudes larger than any conventional phase for continental paths at distances up to 6000 km;
- (4) observed for continental paths only, being gradually eliminated as the ocean path increases beyond 100 km;
- (5) group velocity (near onset) around 3.5 km/s, decreasing to below 2 km/s for periods above 10 s; and
- (6) anomalous dispersion at distances greater than about 20 degrees (that is, frequency decreases for later times in the wave train).

Press and Ewing found that earthquakes as small as magnitude 4.7, at a distance of about 35 degrees, consistently displayed the above properties. In remarking that amplitudes were "larger than any conventional phase," they were presumably comparing Lg to body waves that arrive more-or-less as isolated pulses, and/or to single-mode surface waves that could be identified with a particular dispersion curve.

Press and Ewing noted properties of the three components of ground motion that indicated another type of continental surface wave, which they called Rg, was also being observed with large amplitudes. It had group velocity about 3.05 km/s and the characteristic retrograde elliptical particle motion of a Rayleigh wave.

The reason Press and Ewing labelled these waves Lg and Rg, was that the speeds and some features of the commencement of the observed signals were similar to those predicted theoretically for Love and Rayleigh short-period surface waves in a granitic layer. (That is, for waves at periods shorter than periods seen in conventional teleseismic surface waves.) They attempted quantitatively to show that Lg consists of SH waves multiply reflected within a superficial sialic layer. However, as noted by them and by Lehmann (1953), the idea of such a layer was quickly abandoned (though use of the names Lg and Rg has persisted), because:

- (a) the observed duration of the wave train was much longer than that indicated by Love-wave calculations in a superficial granitic layer;
- (b) Lg was recognized (even in these earliest papers) as having particle motion in vertical and radial directions, as well as in the transverse direction of conventional Love waves; and
- (c) Lg was found to be strong in some earthquakes that originated below the proposed layer - and thus at depths unfavorable for exciting SH multiples that propagate to great distances.

The basic observation that short period Lg has considerable vertical and longitudinal motion was noted in these earliest studies, but not explained except to point out that a plate floating on a fluid substrate would retain SV multiples that arrived concurrently with SH out to great distances.

In retrospect, we may say that Press and Ewing identified what are still recognized as the defining properties of Lg waves. But for many years after these properties were discovered, little progress was made in explaining them quantitatively in terms of synthetics. In contrast, the smaller amplitude "conventional

phases" - body waves and teleseismic surface waves - have been synthesized more and more successfully. Quantitative fits to travel times and waveforms, including normal mode synthesis, have become standard methods for obtaining detailed information about Earth structure, and about earthquake and explosion sources.

However, the fact that Lg can be "larger than any conventional phase" carries its own imperative, whether or not it is a wave that can be fully explained with models of Earth structure and theories of seismic source and wave propagation. For decades, Lg (and Rg) have therefore of necessity been studied empirically by those scientists and engineers whose work inclines to a study of the largest seismic motions. Examples of such empirical work are: many uses of Richter local magnitude,  $M_L$ ; comparative studies of areas of perceptibility of earthquakes in different continental regions; the related subject of how amplitudes of the largest seismic waves vary with epicentral distance; and studies of small magnitude events when only Lg may be apparent above noise levels.

Much pioneering work on Lg waves was done in the 1970s and 1980s by Otto Nuttli of St. Louis University. Thus, Nuttli (1973) proposed that "since Lg represents a higher-mode wave traveling with minimum group velocity" it would be appropriate to relate amplitude (A) and distance ( $\Delta$ ) via

$$A = K[\Delta^{-1/3}][(\sin \Delta)^{-1/2}]e^{-\gamma\Delta} \quad (1)$$

where K is governed by the source strength, and  $\gamma$  is the spatial decay rate due to non-geometrical attenuation. This formula is the stationary phase approximation appropriate for frequencies  $f$  near a minimum in group velocity  $U$ , and

$$\gamma = \pi f / (QU) \quad (2)$$

where  $1/Q$  is a dimensionless measure of attenuation. For values of  $\Delta$  small enough that  $\sin \Delta$  is approximately proportional to  $\Delta$ , i.e. when sphericity of the Earth can be ignored, the geometrical attenuation described by eq.(1) is given by a factor  $\Delta^{-5/6}$ . Nuttli (1973) claimed that the Richter local magnitude scale,  $M_L$ , developed for the western U.S, was based on waves which could be interpreted via eq.(1), but with  $\gamma$  values about ten times higher than the  $\gamma$  values appropriate to use of eq.(1) in fitting observed amplitudes for Lg-waves in eastern North America.

With the goal of defining a magnitude scale for source strength at short periods, based on Lg observations that corrected for path-dependent attenuation, he described in detail (Nuttli 1973, 1986a) a three-step procedure to obtain what he called an  $m_b(Lg)$  value for an earthquake or an explosion of interest. The three steps were as follows:

- (i)  $\gamma$  was estimated for a particular source-receiver path;
- (ii) equation (1) was used to predict an amplitude at one particular distance (he chose  $\Delta$  corresponding to 10 km for reference); and
- (iii) magnitude was assigned via the formula

$$m_b(Lg) = 5.0 + \log [A(10km)/110]$$

where  $A(10 \text{ km})$  is the amplitude, in microns, resulting from (ii).

Nuttli's method is based on a mix of phenomenological properties of observed signals, and theories of Lg propagation. Nuttli specified in detail his procedures for estimating  $\gamma$ : he used a method described by Herrmann (1980), in which the tendency of signal to move to lower frequencies in later portions of the Lg wavetrain is used to obtain Q values -- and Q itself is taken to have a power-law dependence upon frequency. A key assumption of Nuttli's method, namely that geometrical decay of Lg amplitudes is described essentially by a factor  $\Delta^{-6/5}$ , has subsequently been given some support by calculation of synthetics in layered crustal structures (e.g, Campillo et al, 1984).

In order to improve the consistency of  $m_b(\text{Lg})$  estimates resulting from different stations at different distances from the same event (this is the quality referred to as "stability" in the present paper), the measurement that Nuttli actually made from seismograms (short-period WWSSN vertical components) was based on the third largest amplitude in the time window corresponding to group velocities of 3.6 to 3.2 km/s.

For 22 nuclear explosions below the water table at NTS, Nuttli (1986a) showed that his  $m_b(\text{Lg})$  values, using only three WWSSN stations in the western U.S., were remarkably well correlated with the logarithm of announced yield. He proposed a best-fitting line through this magnitude-yield data, from which magnitudes had a standard deviation of only about 0.05. Patton (1988) developed computer-automated measures of Lg amplitude aiming at reproducing Nuttli's NTS results. Patton measured Lg amplitudes from digital seismograms in two ways -- by using the third-largest peak and by computing the RMS amplitude in the Lg time window -- and found very little difference (around 0.01 magnitude unit) in the amount of scatter about regression lines using the two measures. However, he found that standard deviations from best-fitting  $m_b(\text{Lg}) - \log(\text{yield})$  relations were low, 0.07-0.08 magnitude units, only if explosions were restricted to sub-regions of NTS (Pahute Mesa, northern Yucca Flat, southern Yucca Flat).

Based on the success in estimating yields for NTS explosions, Nuttli proceeded to apply the same magnitude-yield relation, together with Lg signals recorded at analogue WWSSN stations in Eurasia, to estimate the yields of nuclear explosions at three Soviet test sites (Nuttli 1986b, 1987, 1988). For the period 1978-1984, after the 150 kt Threshold Test Ban Treaty had gone into effect, his yield estimates for Shagan River explosions included twenty that exceeded the threshold, including one (1982 December 5) estimated by Nuttli to be about 300 kt. While acknowledging the pioneering work involved in these studies, it is clear that the generally low signal-to-noise ratios and the problematic data quality of these analogue recordings made very precise measurements impossible to attain, a fact also recognized by Nuttli himself. Also, at the teleseismic distances for which Nuttli had Lg data, 1900-4400 km, yield estimates based on absolute measures of ground motion that have to be extrapolated back to 10 km are a severe test of the validity of eq. (1), and, even if eq. (1) is appropriate, are very sensitive to errors in  $\gamma$ . Overestimating  $\gamma$  by 10-15% would result in yield estimates about two times too high.

In the first of a number of Lg studies undertaken by the NORSAR staff during the 1980's, Ringdal (1983) analyzed digital NORSAR Lg data of selected

Semipalatinsk underground nuclear explosions. He found that when using NORSAR RMS Lg instead of P waves recorded at NORSAR to estimate source size, it was possible effectively to eliminate the magnitude bias relative to world-wide  $m_b$  observed at NORSAR between Degelen and Shagan River explosions. The method consisted of averaging log (RMS) values of individual NORSAR channels, filtered in a band 0.6 - 3.0 Hz in order to enhance Lg signal-to-noise ratio. Ringdal and Hokland (1987) expanded the data base, and introduced a noise compensation procedure to improve the reliability of measurement at low SNR values. They were able to identify a distinct P - Lg bias between the Northeast and Southwest portions of the Shagan River test site, a feature that was confirmed by Ringdal and Fyen (1988) using Graefenberg array data. Ringdal and Marshall (1989) combined P and Lg based source size estimators to estimate the yields of 96 Shagan River explosions during 1965-1988, using data on the cratering explosion 15 January 1965 as a reference for the yield calculations.

Recent developments have permitted access to high-quality digital data from sites significantly closer to Shagan River, and in addition some information on yields at this test site has become openly available. This obviates the need to make distance corrections to absolute measures of Lg ground-motion amplitude, for purposes of yield estimation at this site. Thus, the focus of this paper will be on using RMS Lg measurements to investigate the stability of this measure for fixed station-source combinations.

#### DATA ANALYSIS FOR SHAGAN RIVER NUCLEAR EXPLOSIONS

Recently data have become available from seven stations located within the Soviet Union and China for explosions in the Semipalatinsk area (see Tables 1 and 2, and Figure 1). These stations are comprised of the IRIS stations (Given and Berger, 1989) the CDSN stations and the Garm station operated by the British as described above. This new data allows the comparison of the stability of the RMS Lg measurement technique for stations at various distances. In particular, we will compare Lg amplitudes of events recorded at the close-in stations with Lg recorded at NORSAR, and P-wave detectability at NORESS.

The seismograms from our data set were all processed in a manner similar to that used for the NORSAR recordings. The processing is illustrated in Figure 2. Figure 2a represents a well recorded event of magnitude  $m_b(P)=5.9$  whereas Figure 2c presents an event of magnitude  $m_b(P)=4.9$ , each as recorded at station ARU. The bottom trace for each event in Figure 2 is the observed data. These seismograms illustrate the broad band character of the typical recordings from modern digital seismometers, where the response is flat from about 5 Hz to well below the frequencies of interest for Lg waves (to between 30 and 100 seconds period for these stations). We first band pass filter the seismograms shown in the bottom trace in the frequency band from .6 Hz to 3 Hz to produce the band passed version in the center of each plot. This is clearly necessary to enhance the Lg waves relative to the longer period microseisms in figure 2b and higher frequency P and Sn coda, as well as to allow comparison to analyses of short period data.

An RMS trace, shown on the top of each plot, is then computed where each point of the trace represents the RMS amplitude measure for the subsequent time window. We then measure the RMS amplitude for the window centered on the phase of interest. In this respect, we did not use a fixed group velocity window for analysis, but rather for simplicity, the same length window of 120 seconds was chosen for all distances and centered near the 3.5 km/sec group velocity arrival time. The RMS measure of Lg was read for the particular 120 second window for all recording stations (and individually for all components of recording). Again for simplicity, the largest value of the RMS trace was chosen as the amplitude measurement as long as the window is still centered near the 3.5 km/sec group velocity. Likewise, an RMS measurement of the noise preceding each event arrival was calculated and applied as a correction term for calculating the Lg amplitude measure as originally defined by Ringdal and Hokland (1987). In contrast to NORSAR, the Soviet and Chinese stations are single site stations, so no averaging of vertical component measures were possible. However, these stations do record three components, which may be averaged. We thus computed both individual component RMS data as well as average values to see whether reduced scatter could be achieved in this way.

Examples of the IRIS recordings are shown in Figures 3 for the JVE event of September 14, 1988. Again, in this Figure are the unfiltered 3 component data along with band pass filtered versions in the frequency range from .6 Hz to 3 Hz. Above each filtered trace we show a 120 second window RMS measure of the amplitude. The first striking feature of the three component seismograms is that the horizontal instruments consistently exhibit a larger amplitude for the Lg phase than the verticals. The closer stations, ARU and GAR, at a distance near 1500 km show this Lg phase as the largest amplitude, while stations OBN and KIV at a distance nearer to 2900 and 2800 km respectively have the P phase as the largest amplitude. The station KIV has no discernible Lg phase for this explosion, presumably because Lg does not propagate efficiently in the crustal structure associated with the Caspian Sea.

The CDSN stations at WMQ and HAI also have well recorded Lg waves. WMQ has an epicentral distance to Shagan River of 950 km, whereas HAI is at a distance of about 2900 km. Both stations show excellent Lg recordings of Semipalatinsk explosions, as illustrated by the examples in Figure 4. Note in particular the dominance of the Lg phase at HAI as the largest recorded phase even at the distance of 2900 km for this azimuth.

Figure 5 compares the signal-to-noise ratios (SNR) (defined as RMS Lg signal to pre-P RMS noise in the 0.6 to 3.0 Hz band) for stations at various distances, using 5 large explosions. The range in magnitude ( $m_b$ ) is from 5.2 for the event on day 317 of 1988 to 6.1 for the JVE event on day 258 of 1988. The event on day 317 indicates the minimum for which RMS Lg was measured at NORSAR at a distance of about 4200 km with a signal to noise ratio of about 1.1. For this same event a signal to noise ratio of about 30 is observable at ARU and GAR at a distance of about 1500 km and about 80 at WMQ at a distance of 950 km. Again, the event at day 258 of 1988 in Figure 5 (shown with the open circle around a plus sign) shows an SNR gain of nearly 100 between NORSAR with an

SNR of 3.5 and WMQ with an SNR of 331. (It should be noted that the low SNR for this event at ARU is due to the fact that this event was only recorded on the low gain channel which does not adequately resolve the background noise.) It is noteworthy that WMQ shows the best SNR for all the events. The figure suggests that WMQ, if set to record continuously, would be able to give Lg measurements for events close to two magnitude units smaller than the NORSAR threshold of approximately 5.5. Unfortunately, there were no low magnitude events for WMQ in our data base, so we have not been able to confirm this hypothesis. We do, however, show an example of an  $m_b(P)$  3.8 explosion, whose Lg signal was recorded by ARU (see below).

In order to verify the stability of the RMS Lg amplitudes observed at the Soviet and Chinese stations, the amplitudes were compared with NORSAR amplitudes for common events. Since the instrument response of the different IRIS stations was changed several times, and was different at different stations (each being different from that of a NORSAR station), we decided to convert all measurements of IRIS stations to the equivalent gain of a typical NORSAR short period instrument in the .6 to 3 Hz range. The CDSN stations and station GAM had a constant gain throughout the recording period of this study, so no gain adjustment was required.

The variation of RMS Lg amplitudes as a function of event size and distance is illustrated in Figures 6 and 7. First, in Figure 6, we compare the difference in RMS Lg between two events recorded at the same stations. The stations are NORSAR (~ 4200 km), ARU (~ 1500 km), and OBN (~ 2900 km) for the JVE event minus the  $m_b$  5.9 event on day 352 of 1988. We first note that all three stations indicate that the JVE has a larger Lg signal by about 0.2 magnitude units, and the observations are thus quite consistent. Furthermore, we see a variation among the three components of ARU and OBN typically on the order of .07 magnitude units. However, the average of the three components is more stable compared to NORSAR, with a variation of only about 0.02 magnitude units. From observing the behaviour of similar plots for other events it appears that averaging the three components may indeed provide a consistent gain in stability, but we have in this study concentrated on obtaining statistics using the vertical components only.

For comparison of actual measurements of RMS Lg amplitudes between NORSAR and four of the new stations (ARU, GAM, WMQ, and HAI) for all common events, we plot in Figure 7 data for the vertical component of RMS Lg. A straight line has been fit to the data for each of the four stations and a measure of the misfit is given by an orthogonal standard deviation (dotted line on the Figure corresponds to 2 standard deviations).

Figure 7 a,b, and c show the comparison of GAM, ARU, and WMQ versus NORSAR log RMS (Lg) estimates for all common events. The slopes of these plots are 0.92, 0.96, and 1.03 respectively with orthogonal standard deviations of the misfits being only 0.035, 0.022, and 0.024 units.

Figure 7d shows a comparison of HAI and NORSAR log RMS (Lg) estimates. In this case, the slope of the least squares linear relationship (1.48) is significantly different from unity, and we note that a similar observation was also made by

Ringdal and Marshall (1989) when comparing NORSAR and Graefenberg Lg. We will not go into any detail discussing possible underlying physical reasons for this variability in slopes. For our purpose, the important point is to note that the scatter of the relationship is still very small; the orthogonal standard deviation relative to the straight line fit is 0.023, which in fact compares very closely to the results found above for the other station pairs. The fit between HAI versus WMQ log RMS (Lg) values again gives a least-squares slope (1.36) that is significantly different from unity. Once more, however, the scatter is very small, with an orthogonal standard deviation of 0.028 units. We thus find essentially the same scatter for all data when comparing different station pairs and this confirms the excellent stability of the RMS Lg estimates when considering a suite of explosions within the limited source region of the Shagan River area.

In Figure 8a we plot the RMS Lg amplitude at WMQ against world-wide  $m_b(P)$  magnitudes for all recorded events at Shagan River. The slope is 1.02 and the orthogonal standard deviation is 0.044. This scatter is also quite small, but it must be noted that only one event from the northeast part of Shagan is in the data base. Thus, we cannot assess whether the  $m_b(Lg)$  versus  $m_b(P)$  bias earlier found for this subregion (Ringdal and Marshall, 1989) is also present when measuring Lg at WMQ. For comparison we have also plotted in Figure 8b the same  $m_b(P)$  estimates against the logarithm of the largest Pn amplitude at WMQ measured within the first 5 seconds of the first arrival. Here we see a much larger scatter for the single station than for the RMS Lg amplitudes. This is consistent with previous studies of teleseismic P at single stations. For example, Lilwall et. al. (1988) found a typical standard deviation of 0.12  $m_b$  units when comparing single station  $m_b$  to world wide  $m_b$  for a set of Shagan River explosions.

As a contrast to these well recorded events, Figure 9 illustrates the capabilities of the ARU station to record an  $m_b(P)$  3.8 event from the Shagan River test site on day 270 (September 26) of 1988. (This magnitude is based on the NORSAR  $m_b(P)$  of 4.3 with an assumed regional correction of 0.5 units for comparison to world wide  $m_b$  estimates and therefore must be considered somewhat uncertain). The unfiltered broad band trace at ARU essentially shows no signal for this event, however the band pass filtered trace clearly shows energy arriving that can be identified as Lg with a signal to noise ratio of about 2. (Similar SNR was obtained for the recording at GAM for this event.) This SNR is near the lower limit of about 1.5 for allowing reliable RMS Lg estimates at a single site. In an attempt to enhance the detectability of other phases, the vertical component of ARU was filtered in several pass bands as illustrated in Figure 10. Even considering frequency bands up to the Nyquist frequency of 10 Hz we found no additional enhancement of the P phase or other phases. (It may be noted that ARU is at a distance within a shadow zone for P waves from seismic sources in East Kazakhstan.) In comparison, the NORESS array is clearly capable of detecting the P wave arrival with an SNR of nearly 30 as illustrated in Figure 11 and the ARCESS array also shows a clear P-detection for this event. Thus, even though the ARU station may not be capable of detecting an event of this size in an automatic fashion, regional arrays such as NORESS and ARCESS can correctly detect the event while the analysis of the Lg phase at a much closer station can

provide an estimate of the RMS Lg magnitude suitable for giving independent information on explosion yield.

Figure 12 illustrates the stability of the RMS Lg amplitudes by comparing GAM and ARU. These stations are chosen as they are the only pair for which we have Lg recordings of the  $m_b(P)$  3.8 event shown in Figures 9-11 and so illustrate the stability of measurement covering a span of two full magnitude units. Here we again have a slope of very nearly one still with an orthogonal standard deviation of only 0.026 logarithmic units (i.e. magnitude units).

## DISCUSSION

A heuristic explanation for the superior stability of Lg, as compared to stability of P, lies in the difference in the nature of the sampling of the seismic source for each of these phases. P-waves for each source-station pair sample only a very limited portion of the focal sphere and are susceptible to focussing and defocussing, so to get an improved average using P-waves it is necessary to use many stations around the globe and even so, when using a teleseismic network, only a relatively small part of the focal sphere will be sampled. But Lg waves are composed (for each source-station pair) of multiple rays that sample a larger portion of the focal sphere and therefore the Earth is doing the averaging for us.

In demonstrating that a single station can provide RMS Lg measurements with a precision (one standard deviation) of about 0.03 magnitude units at Shagan River, we note that several issues are raised in considering how best to use such measurements for yield estimation.

For example, there are general questions concerning how to define  $m_b(Lg)$ : can we carefully define an  $m_b(Lg)$  scale that is indeed a property of seismic sources, and then establish a procedure by which  $m_b$  on this scale can be estimated by measurements made with one or more stations in a seismograph network? One way to proceed, would be to define  $m_b(Lg)$  as the measurement made in a particular way with a particular seismographic network. The  $m_b(Lg)$  for a particular seismic event could then be directly measured (to the extent that the full network supplied data), or instead estimated if only a subset of the data were available -- for example, from only a limited number of stations.

Fortunately, in many projects in which a suite of seismic events is under study, an accurate estimate of absolute  $m_b(Lg)$  values is not needed. Rather, one may only need estimates of the *relative*  $m_b(Lg)$  values. The key quality needed is precision of measurement: absolute levels are unimportant or may be derived from separate information. This is the situation, for example, in making yield estimates based on seismic data for a suite of underground nuclear explosions at a particular test site, if independent (perhaps non-seismic) information on the yield of some of the events is made available. This information can be used to calibrate in absolute terms a seismic amplitude scale that may be defined uniquely for a particular source region, and for a particular network of stations. In this context, in claiming in this paper that the stability of RMS Lg is excellent, we mean that relative magnitudes of explosions in the same region can be estimated very



accurately from one or two stations that record Lg, if signal-to-noise level is high enough.

However, for other purposes we recognize that there is a need to work with absolute rather than relative  $m_b(Lg)$  values. For sources and receivers at any location on the same continent (Lg does not propagate across oceans), the need eventually is to understand how to make path corrections to RMS Lg measurements, for purposes of assigning  $m_b(Lg)$  as a characteristic directly of source strength. It is clear that such corrections will depend on both source and receiver locations, and not merely on the scalar distance. (As noted above, Nuttli did begin the process of making specific path corrections, by making a correction for Q effects.) Obtaining accurate path corrections depending on four spatial coordinates (depth is a separate issue), whether determined empirically for each path or by predictions based on data from a coarse grid of sources and receivers, is certain to be a complex procedure. However, it is likely too to be associated with discovery of much new information about continental crustal structure. Our point here is that the precision of RMS Lg measurements presents new challenges and new opportunities.

Assigning absolute levels of  $m_b(Lg)$  for nuclear explosions at a fixed test site and for a fixed network is a far simpler task -- one that we have addressed in this paper without special comment. While we have not discussed the problem of converting RMS Lg to a magnitude value, this is a relatively straightforward task, implying calibration to a given magnitude scale. Presuming that magnitude in this sense, and yield, are related at the test site by a best-fitting line in the form

$$m_b(Lg) = a + b \cdot \log(\text{yield}),$$

it is clear that the scatter of points about this line is controlled by two factors. One is the precision with which  $m_b(Lg)$  can be measured (for example 0.03 at a single station, as shown in this paper for the Shagan River area). The second is the additional uncertainty caused by variability of coupling from nuclear yield into Lg signal, a key issue that at present we are not in a position to resolve.

Assistance in addressing the second issue would come from open availability of yield information for some explosions at test sites of interest, preferably for the same explosions whose seismic signals were recorded at high-quality digital stations. We note that yields are not currently announced at the world's two main test sites (the Nevada Test Site, and at Shagan River), and yields announced at these sites for explosions in the past (Springer and Kinnaman, 1971, 1975; Bocharov et al, 1989; Vergino, 1989ab) were for the period prior to 1973 when few digital stations were in operation. However, preliminary indications, from a study of the four Semipalantinsk explosions for which there is both an announced yield from Bocharov et al (1989) and an RMS Lg signal measurement at NORSAR, are that RMS Lg correlates well with  $\log(\text{announced yield})$  (Ringdal, 1989). This comparison can be used for example to estimate the yield of the Joint Verification Experiment (JVE) explosion, conducted at Shagan River on 1988 September 14. From NORSAR Lg signals alone, the resulting estimate would be about 110 kt. As yet, the yield of this explosion, as determined from non-seismic measurements made on-site, has not been announced, other than that it met the provisions of

the JVE agreement between the U. S. and the U.S.S.R., and thus that it was indeed between 100 and 150 kt (Robinson, 1989).

An important advantage of the RMS Lg method is its ease of use, in combination with the robustness of the results. Thus, it makes essentially no difference whether one uses a two-minute window, or one based on a range of Lg group velocities (which would give a window about 40 sec at ARU for the range of group velocity used in NORSAR analyses). Also, the choice of filter band is not critical as long as the band enhances the main part of the Lg energy and is kept fixed in the analysis of different events. Our choice of a 0.6-3.0 Hz passband has been made in order to be consistent with previous NORSAR analyses.

### CONCLUSIONS

This study has demonstrated that RMS Lg amplitudes estimated from stations within the Soviet Union and China for Shagan River explosions show excellent consistency with NORSAR RMS Lg estimates. This has several important implications:

1. RMS Lg appears to be a stable source size estimator when computed at widely distributed stations, and would therefore provide a reliable magnitude estimate once the proper correction term has been estimated for each station.
2. The stations studied (notably ARU, GAM, and WMQ) can be used to estimate Lg magnitudes for Shagan River explosions of much lower yield than is possible using the more distant NORSAR and Graefenberg arrays. Our analysis indicates that the signal to noise ratio improvement allows RMS Lg estimates to be made down to approximately  $m_b$  3.5 at WMQ, compared to a threshold of about  $m_b$  5.5 at NORSAR. An important precondition for WMQ is that it be set to provide continuous recording, rather than the triggered recording currently used.
3. Although single stations do not offer the increased stability obtained through array averaging, this is partly compensated by the higher signal to noise ratio, which means that modest noise fluctuations will be insignificant for the Lg measurements. Also, a possibility of decreasing scatter of magnitude estimates through averaging the three components of each station exists. Our initial analysis indicates that such an approach could be useful, but it may be necessary to determine correction terms for each component individually.
4. As more data (and possible additional stations) become available, a data base will be developed that will enable us to compute network averages, based on individual station data "calibrated" to NORSAR  $m_b$ (Lg). This would facilitate both obtaining improved uncertainties of future explosions, and maintaining a comparison to historic data. The calibration would best be done using direct, independent, yield information, thus permitting reduced uncertainties in yield estimation (using seismic methods) for future explosions.
5. The P-wave detection capabilities of these single stations do not match those of the NORESS and ARCESS arrays, thus teleseismic signals continue to be important for detection of small nuclear explosions.

It would be desirable to develop a theoretical basis to allow correction for attenuation of the Lg phase. Extension of the study to other nuclear explosion sites will also be an important topic. Of particular interest here is to study further the possible differences between the Shagan River and Degelen Mountains region.

In conclusion, our studies confirm that Lg magnitude estimates of Semipalatinsk explosions are remarkably consistent between stations widely distributed in epicentral distance and azimuth. It thus appears that a single station with good signal-to-noise ratio can provide  $m_b(Lg)$  measurements with an accuracy (one standard deviation) of about 0.03 magnitude units. Therefore, Lg signals appear to provide an excellent basis for supplying estimates of the yields of nuclear explosions even down to below one kiloton, when such signals are recorded at high-quality digital in-country seismic stations, and when calibrated by access to independent (non-seismic) yield information for a few nuclear explosions at the test sites of interest. In the context of monitoring a low yield threshold test ban treaty, it will, in addition, be important to take into consideration various environmental conditions in the testing area, such as the possible presence of cavities, and to devise appropriate procedures for on-site observations in this regard.

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Station	Latitude	Longitude	Elevation (m)
WMQ	43.821 N	87.695 E	970
HAI	49.267 N	119.742 E	610
ARU	56.40 N	58.60 E	250
GAR	39.00 N	70.32 E	1300
KIV	43.95 N	42.68 E	1206
OBN	55.10 N	36.60 E	160
GAM	39.00 N	70.19 E	1300

Table 1 Seismographic Station locations

No.	Date	$m_b$	NAO Lg	WMQ Lg	HAI Lg	ARU Lg	GAR Lg	KIV Lg	OBN Lg	GAM Lg
1	87171	6.03	3.012	3.851	2.189	-	-	-	-	-
2	87214	5.83	2.911	3.693	2.072	-	-	-	-	-
3	87319	5.98	3.014	3.870	2.298	-	-	-	-	-
4	87347	6.06	3.133	3.907	2.352	-	-	-	-	-
5	87361	6.00	3.086	3.851	2.334	-	-	-	-	-
6	88044	5.97	3.082	3.911	-	-	-	-	-	-
7	88094	5.99	3.103	3.925	2.307	-	-	-	-	-
8	88125	6.09	3.084	3.958	-	-	-	-	-	-
9	88258	6.03	3.014	3.827	2.224	4.142	3.802	3.014	3.342	3.184
10	88270	3.8	-	-	-	2.215	-	-	-	1.196
11	88317	5.20	2.307	3.104	-	3.429	3.165	-	-	2.521
12	88352	5.80	2.846	3.636	1.947	3.935	-	-	3.191	3.034
13	89022	6.0	3.005	-	-	4.075	-	-	-	3.161
14	89043	5.90	2.836	3.619	1.921	3.891	-	-	3.228	2.923
15	89189	5.60	-	-	-	3.562	3.326	2.609	2.823	-
16	89292	5.9	2.834	-	-	3.942	-	-	3.208	-

Table 2 Magnitudes ( $m_b$ ) and log RMS Lg values for vertical components at stations NORSAR, WMQ, HAI, ARU, GAR, KIV, OBN, and GAM for 16 explosions analyzed in this study. Note that the IRIS stations ARU, GAR, KIV, and OBN have been normalized to a constant gain level to adjust for response changes. The values for the three stations WMQ, HAI, and GAM reflect unadjusted count values of the raw seismograms.

## FIGURE CAPTIONS

**Figure 1** Map indicating the locations of the Shagan River Test Site, the IRIS and British stations in the USSR, the NORSAR array in Norway and the stations WMQ and HAI in China. The NORESS array is collocated near the NORSAR array, and the station GAM is collocated near the GAR station.

**Figure 2** Example of recordings from two Soviet nuclear explosions at the IRIS station ARU. a) An  $m_b$  5.9 event at Shagan River on 19 October 1989 illustrating a good signal-to-noise ratio, and b) an  $m_b$  4.9 event at Degelen Mountains to illustrate the improvement in signal-to-noise ratio by bandpass filtering in the range 0.6 to 3.0 Hz. For each of the events, we show the unfiltered trace (bottom), the filtered trace (0.6–3.0 Hz) (middle), and the 120-second window RMS measure (top) as a function of time.

**Figure 3** Plots of the data recorded on the four IRIS stations located in the USSR for the Soviet JVE explosion of September 14, 1988. For each of three components at each site we show the unfiltered trace (bottom), a filtered version in the band 0.6 Hz to 3.0 Hz (middle), and the 120 second window RMS amplitude measure (top) as a function of time.

**Figure 4** Example of recordings from two Soviet nuclear explosions at the two CDSN stations. a) 3 April 1988 at station WMQ and b) 14 September 1988 at station HIA. For each of the three components we show the unfiltered trace (bottom), the filtered trace (0.6–3.0 Hz) (middle), and the 120-second window RMS measure (top) as a function of time.

**Figure 5** Graph showing the variation of the signal-to-noise ratios ( $\log \text{RMS } L_g$  minus  $\log \text{RMS noise}$ ) among the four IRIS stations, the NORSAR array and the CDSN stations WMQ and HIA. Epicentral distance to the Shagan River test site is plotted along the horizontal axis.

**Figure 6** The difference in RMS  $L_g$  amplitudes (or magnitudes) between the Soviet JVE explosion on September 14, 1988 and the  $m_b$  5.9 explosion on December 17, 1988 for two IRIS stations and the NORSAR array. The IRIS stations show vertical (8 point star), N-S (triangle), and E-W (box) components and the average (6 point star). The NORSAR point represents the average of readings from vertical instruments.

**Figure 7** Comparison of  $\log \text{RMS } L_g$  at NORSAR with RMS  $L_g$  measurements obtained at four of the close-in stations. a) GAM with a fitted slope of 0.92 and an orthogonal RMS misfit of .035 magnitude units, b) ARU with 0.96 and 0.022, c) WMQ with 1.03 and 0.024, and d) HAI with 1.48 and 0.023. The dotted lines correspond to plus or minus two standard deviations.

**Figure 8** a) Comparison of  $\log \text{RMS } L_g$  at WMQ to world-wide  $m_b$  magnitude. Standard deviation is 0.044 orthogonal to the line. b) Plot showing the WMQ  $\log P_n$  amplitude measured within the first five seconds of the  $P_n$  arrival against world-wide  $m_b$ . The slope of the straight line has been fixed to 1.0. The orthogonal

standard deviation is 0.140. The dotted lines correspond to plus or minus two standard deviations.

**Figure 9** The ARU vertical component seismogram from the  $m_b$  3.8 explosion on September 26, 1988. The lower trace is the unfiltered seismogram, the middle trace is the band pass filtered seismogram between 0.6 Hz and 3.0 Hz, and the upper trace is the RMS amplitude as a function of time.

**Figure 10** The ARU vertical component seismogram from the  $m_b$  3.8 explosion on September 26, 1988. The top trace is the unfiltered seismogram, while subsequent traces show the results after filtering in successively higher band pass frequency intervals.

**Figure 11** Example of four vertical component seismograms from the NORESS array in Norway for the  $m_b$  3.8 explosion on September 26, 1988. Shown on the bottom trace is the beam formed by steering toward the explosion site. Note the large improvement in signal-to-noise ratio on the beam.

**Figure 12** Comparison of log RMS  $L_g$  measurements at ARU and GAM. The slope of the line is 1.04 and the standard deviation of the misfit of the line to the data is 0.026 orthogonal to the line. The dotted lines correspond to plus or minus two standard deviations. Note the remarkable stability of measurement between the two stations over two full magnitude units.



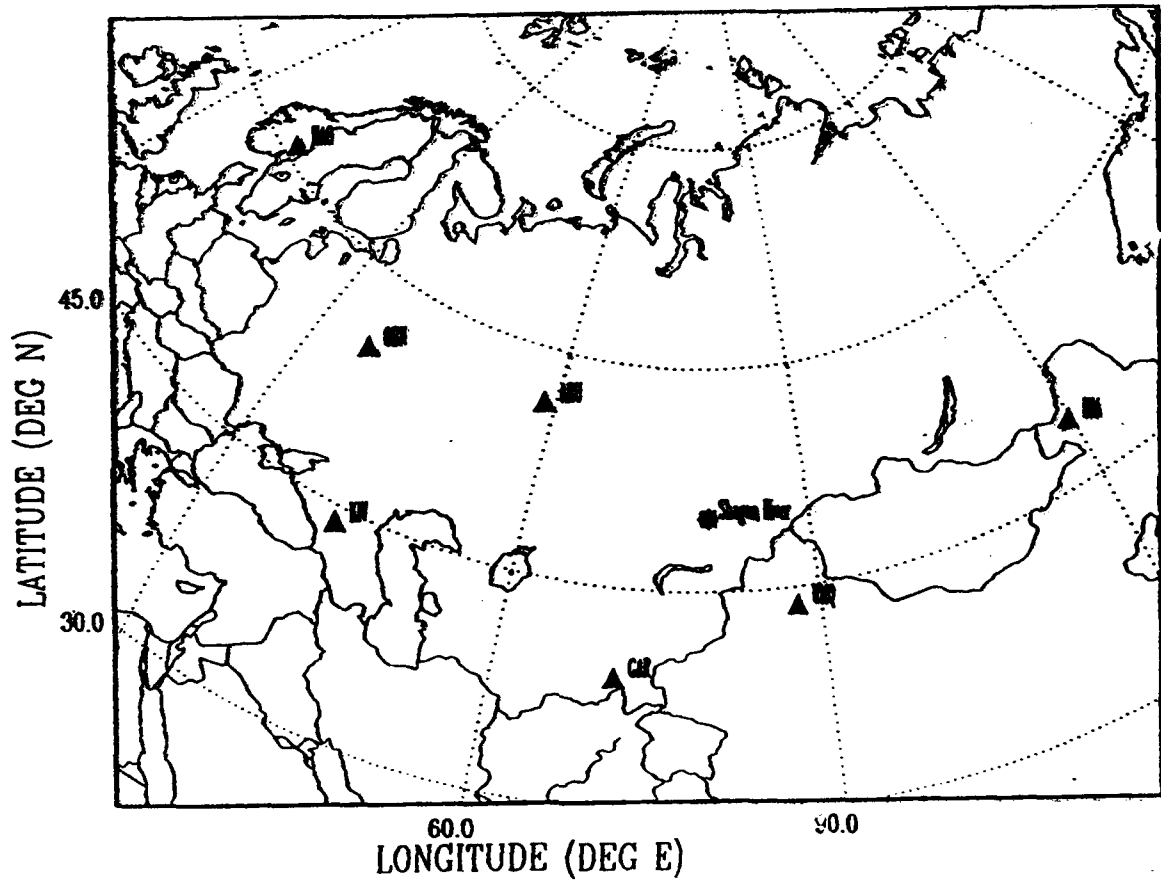
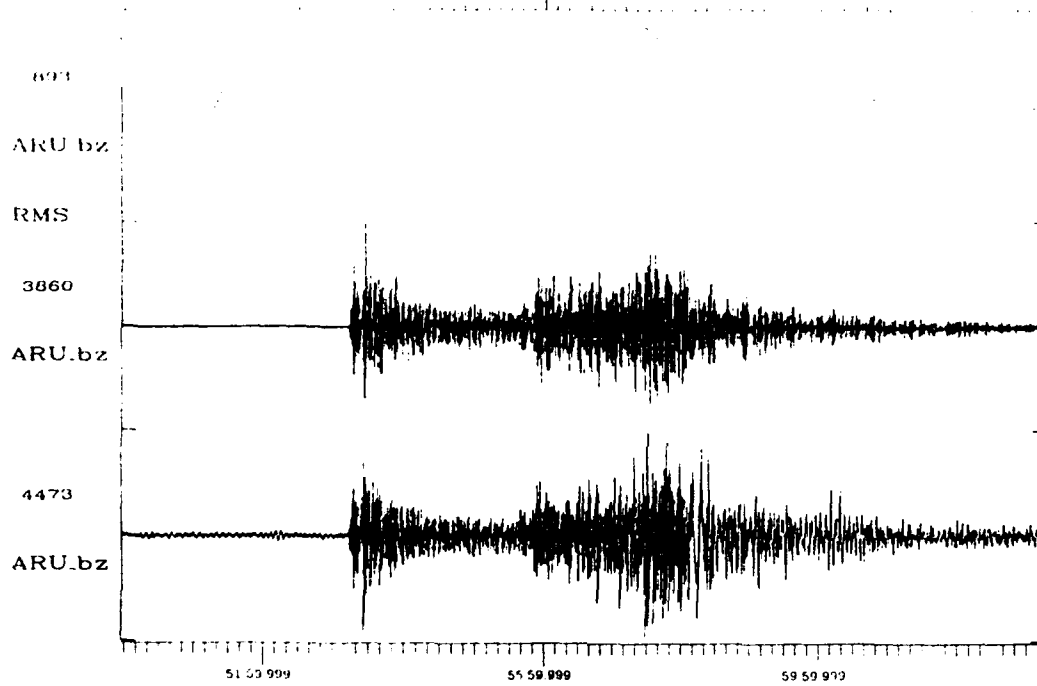


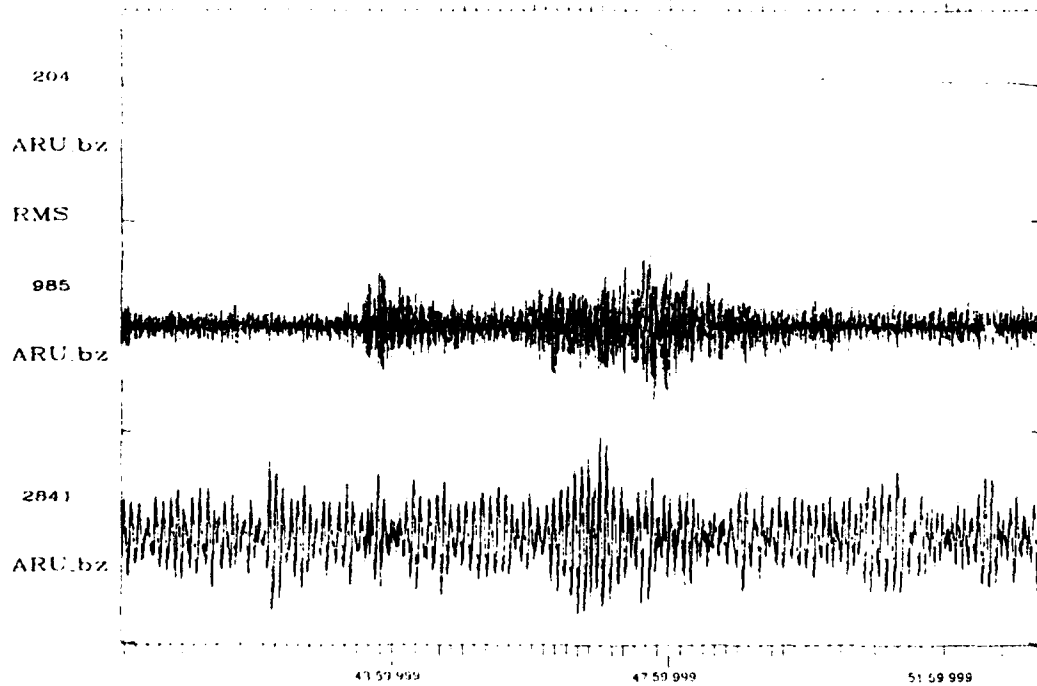
FIGURE 1

mb 5.9 Event at Semipalatinsk



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mb 4.9 Event at Semipalatinsk



1988 292 03 40 06 600

FIGURE 2

### Semipalatinsk 14.09.88

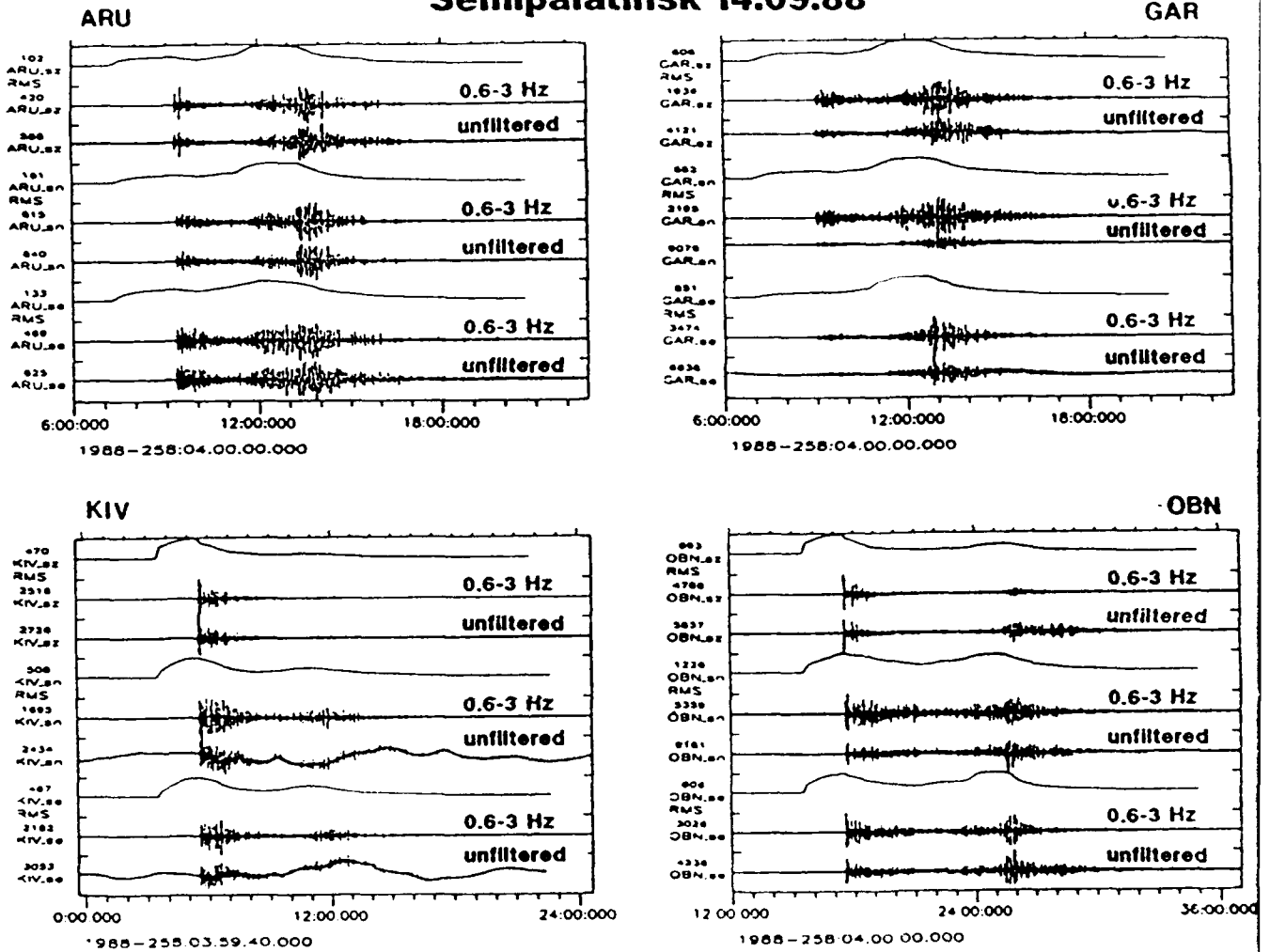
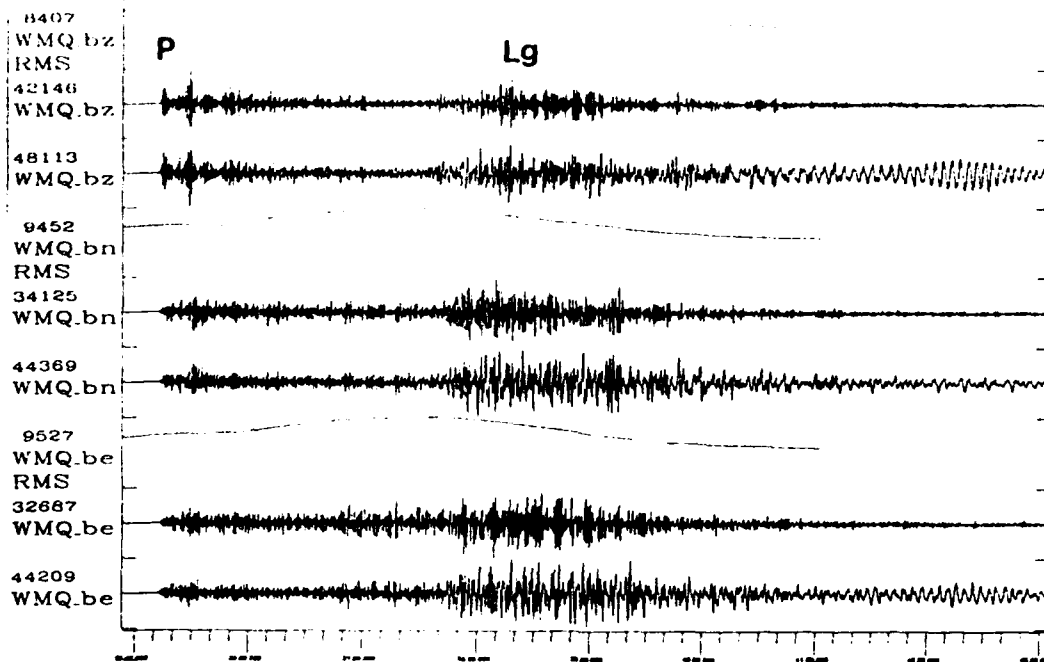


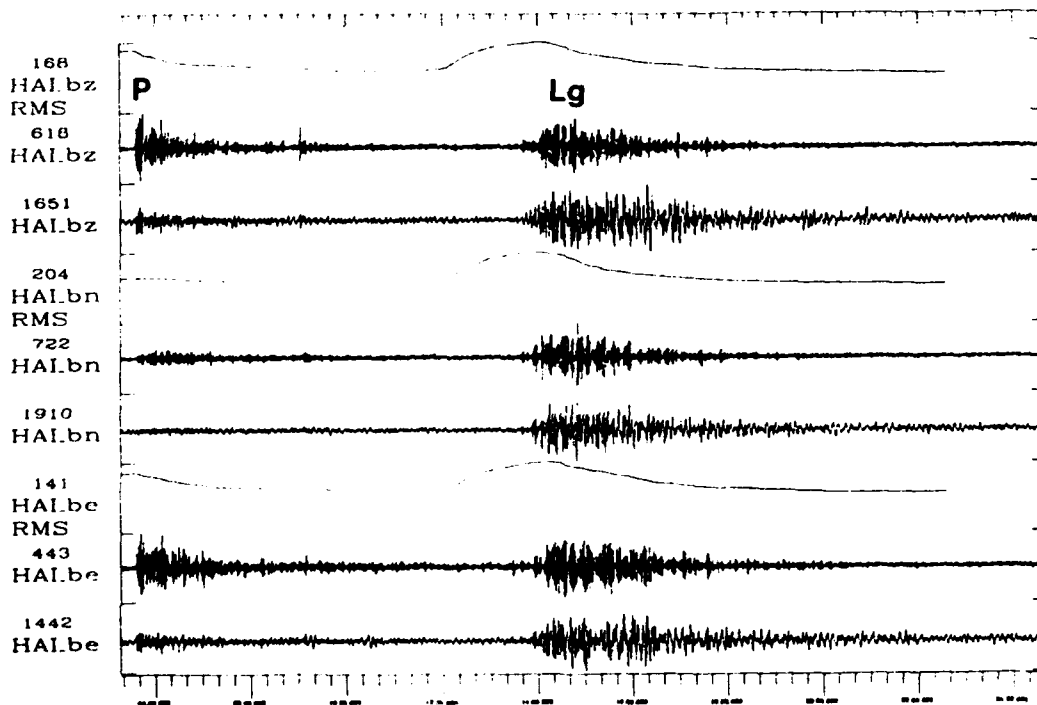
FIGURE 3

a



1988 094.01.34.53.010

b



1988-258 04.05.15 990

FIGURE 4

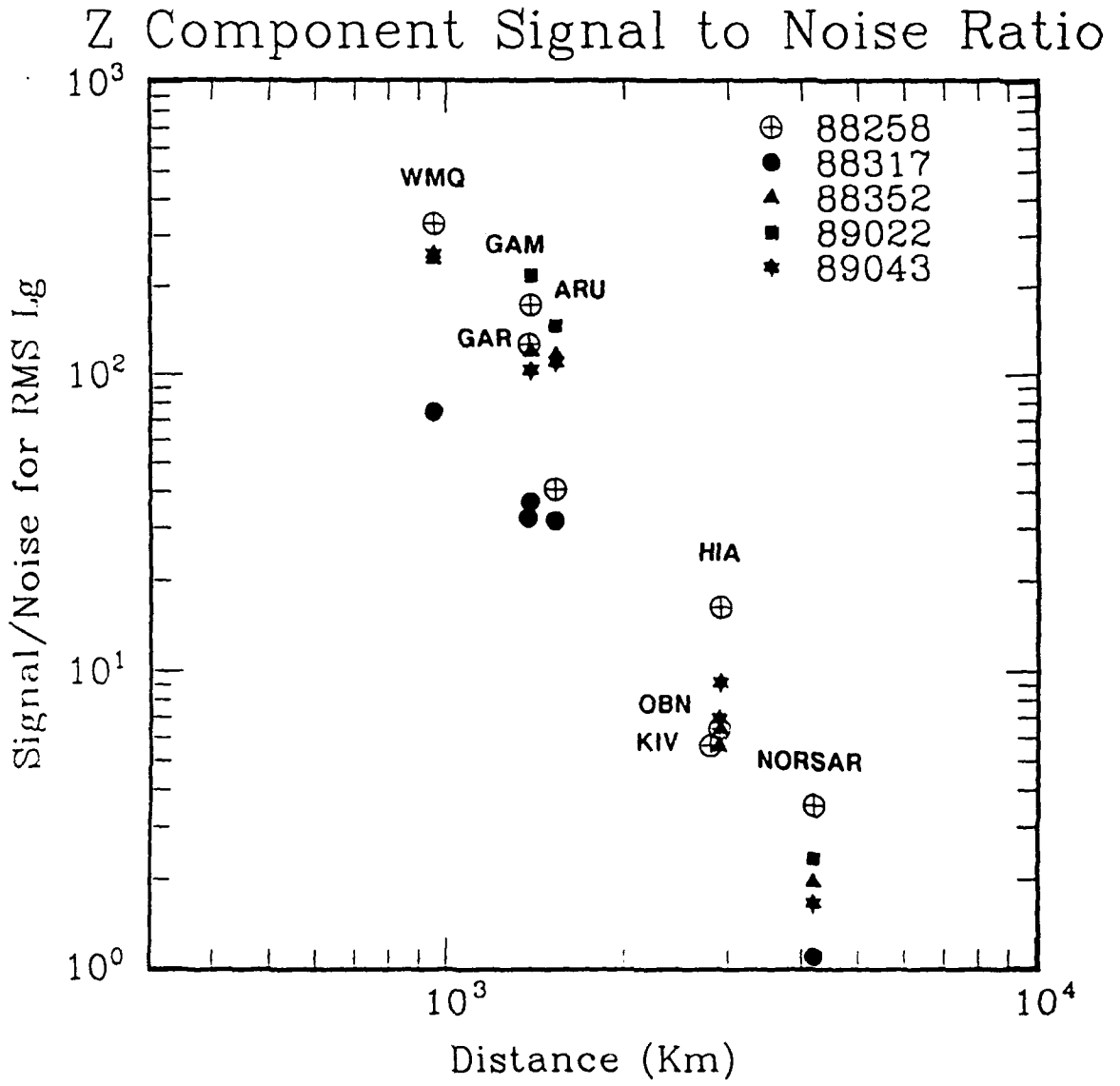


FIGURE 5

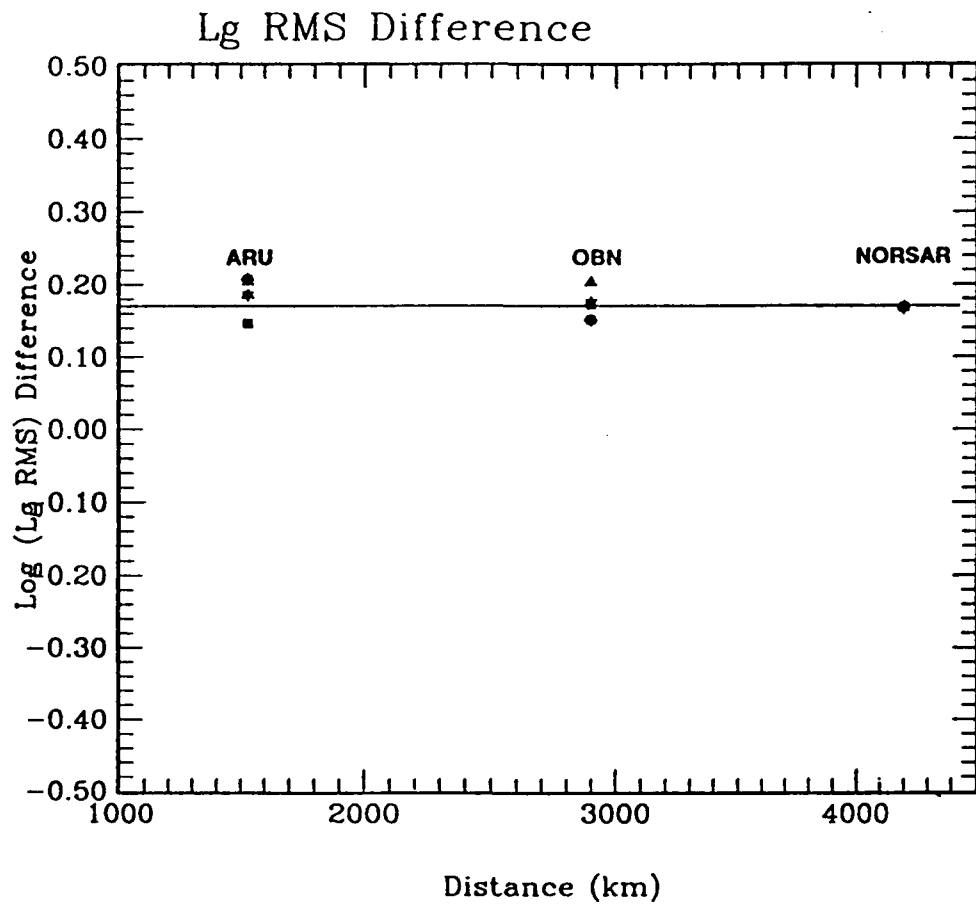


FIGURE 6

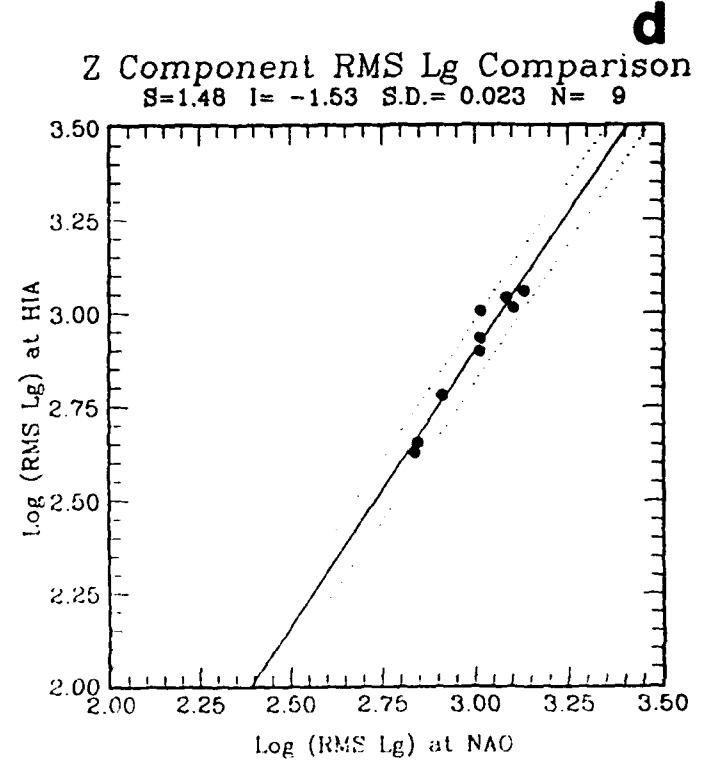
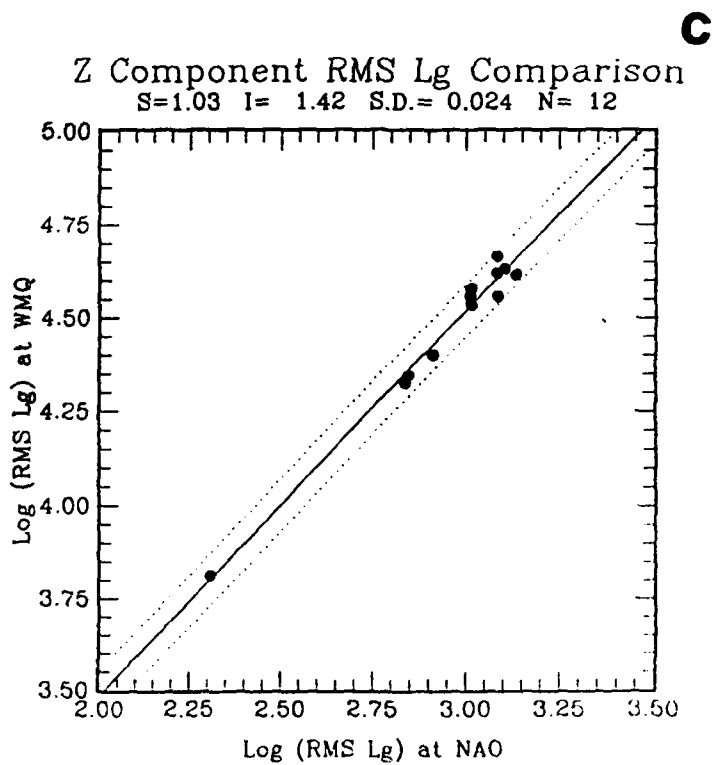
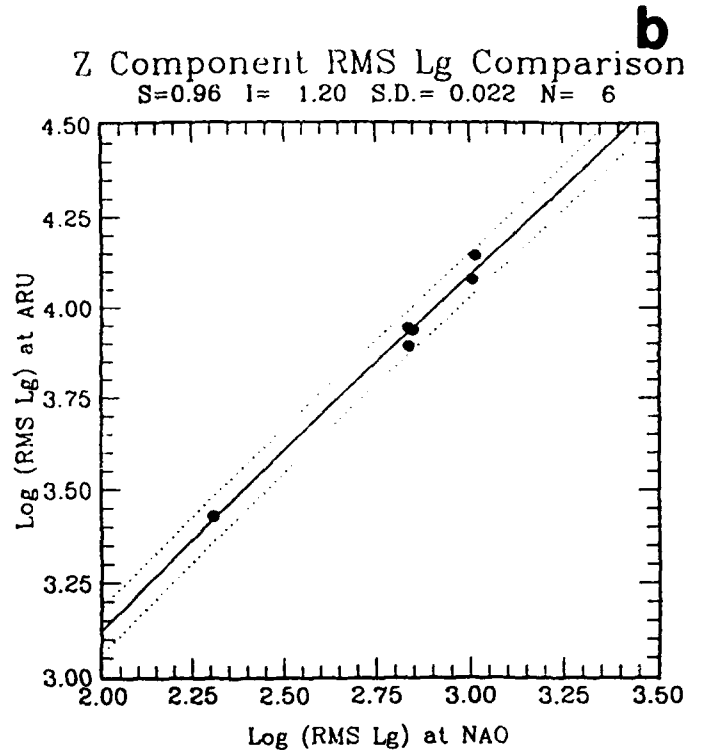
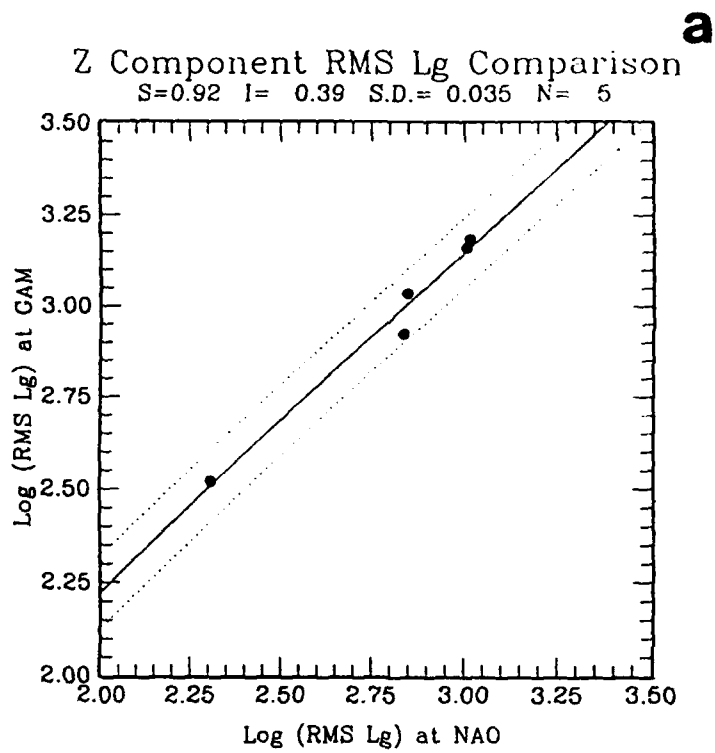
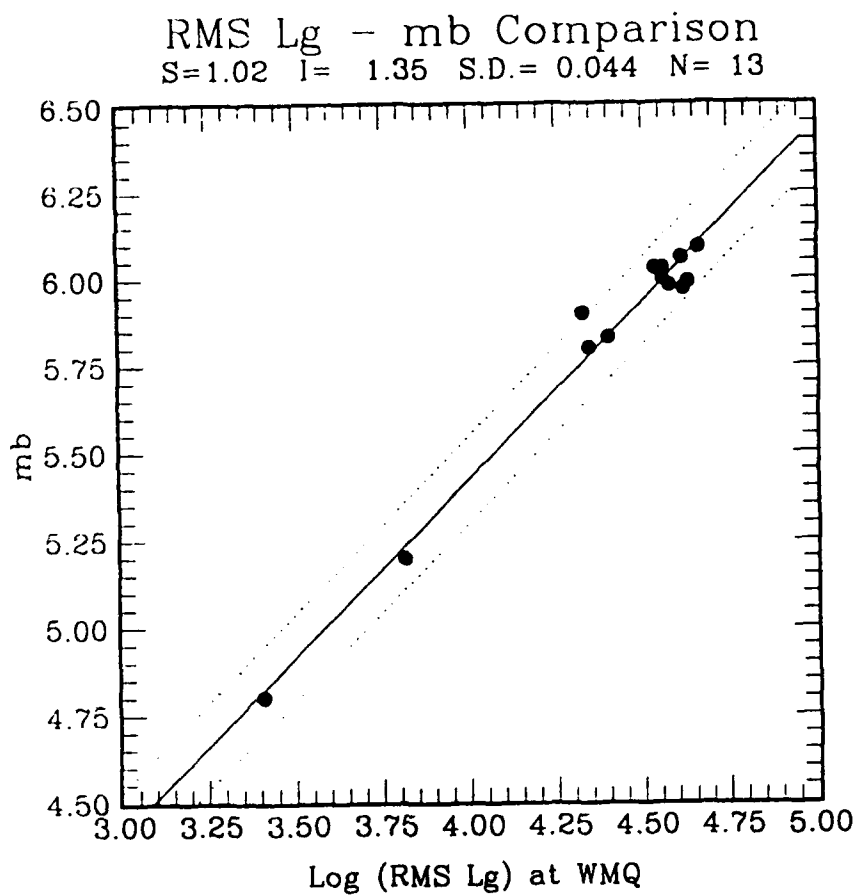


FIGURE 7

a



b

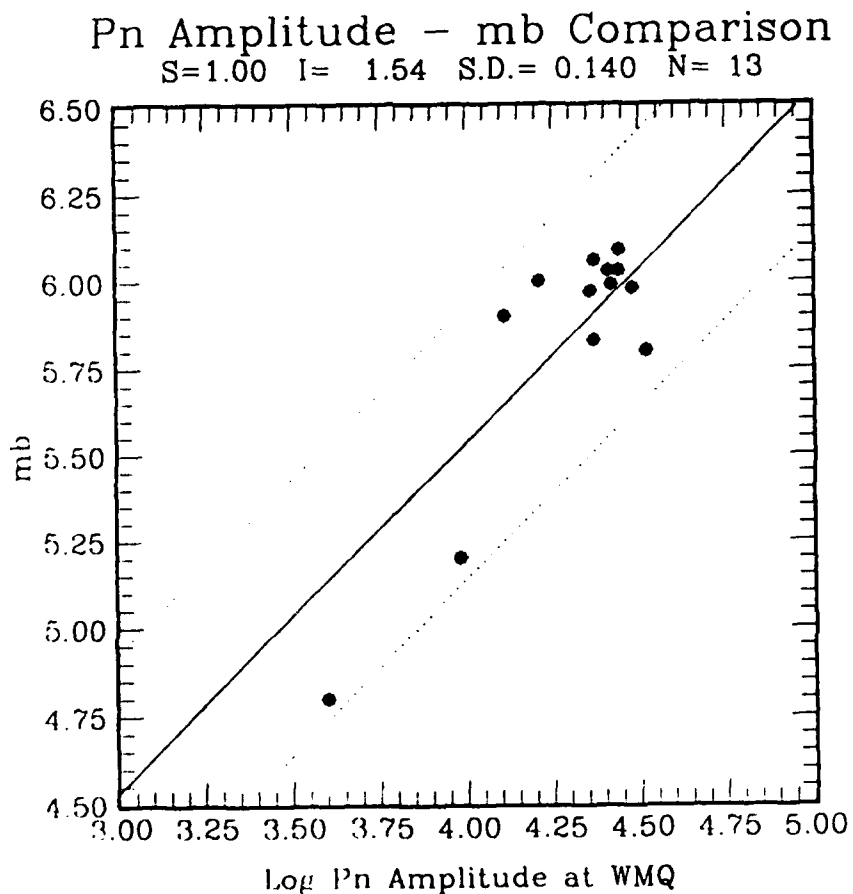
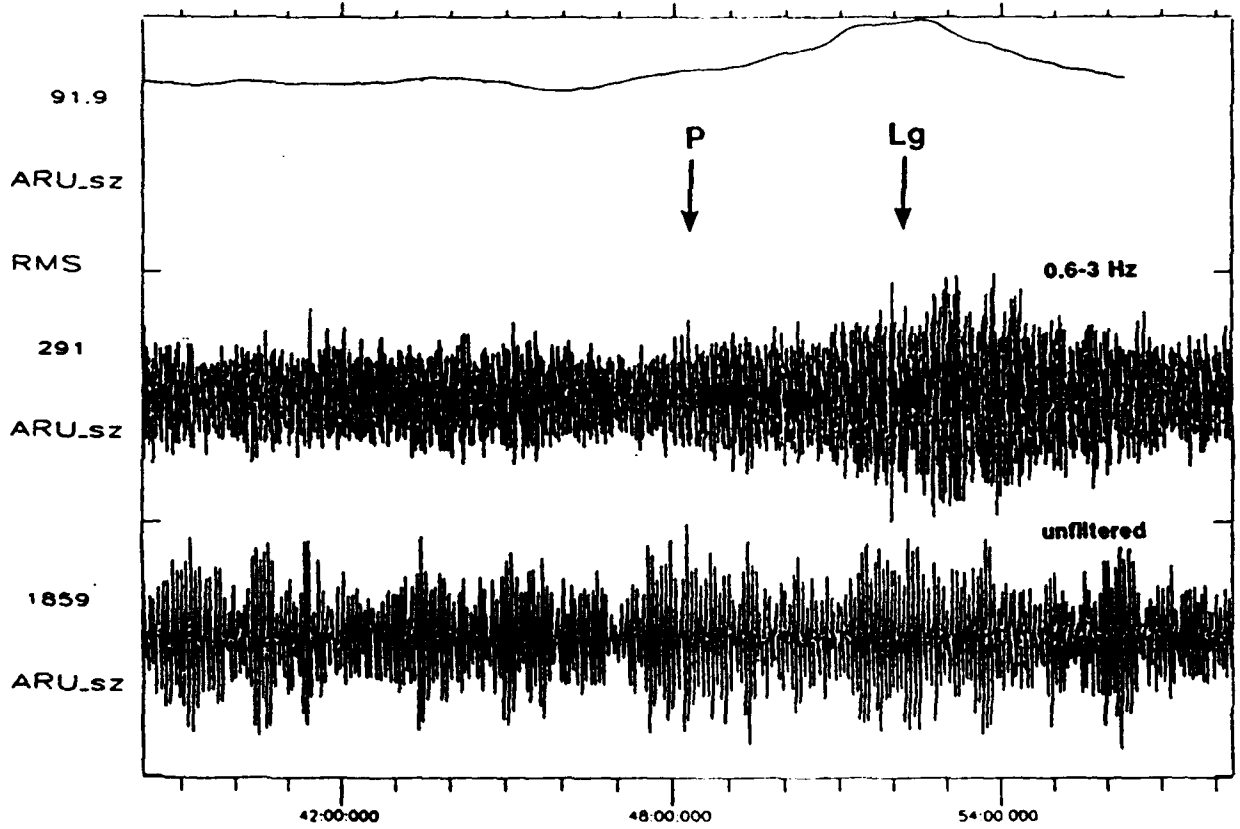


FIGURE 8



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FIGURE 9

### Semipalatinsk 9/26/88

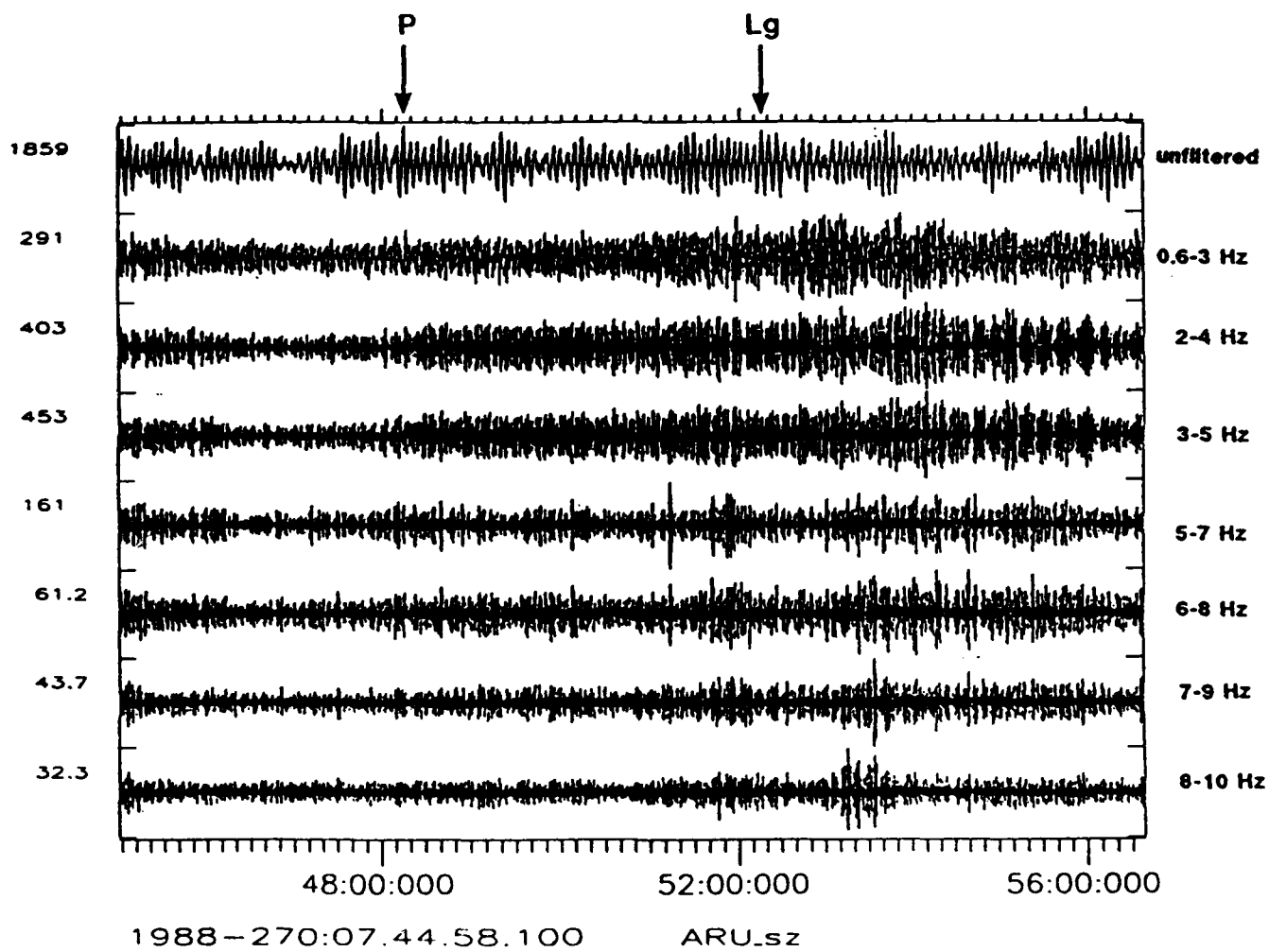
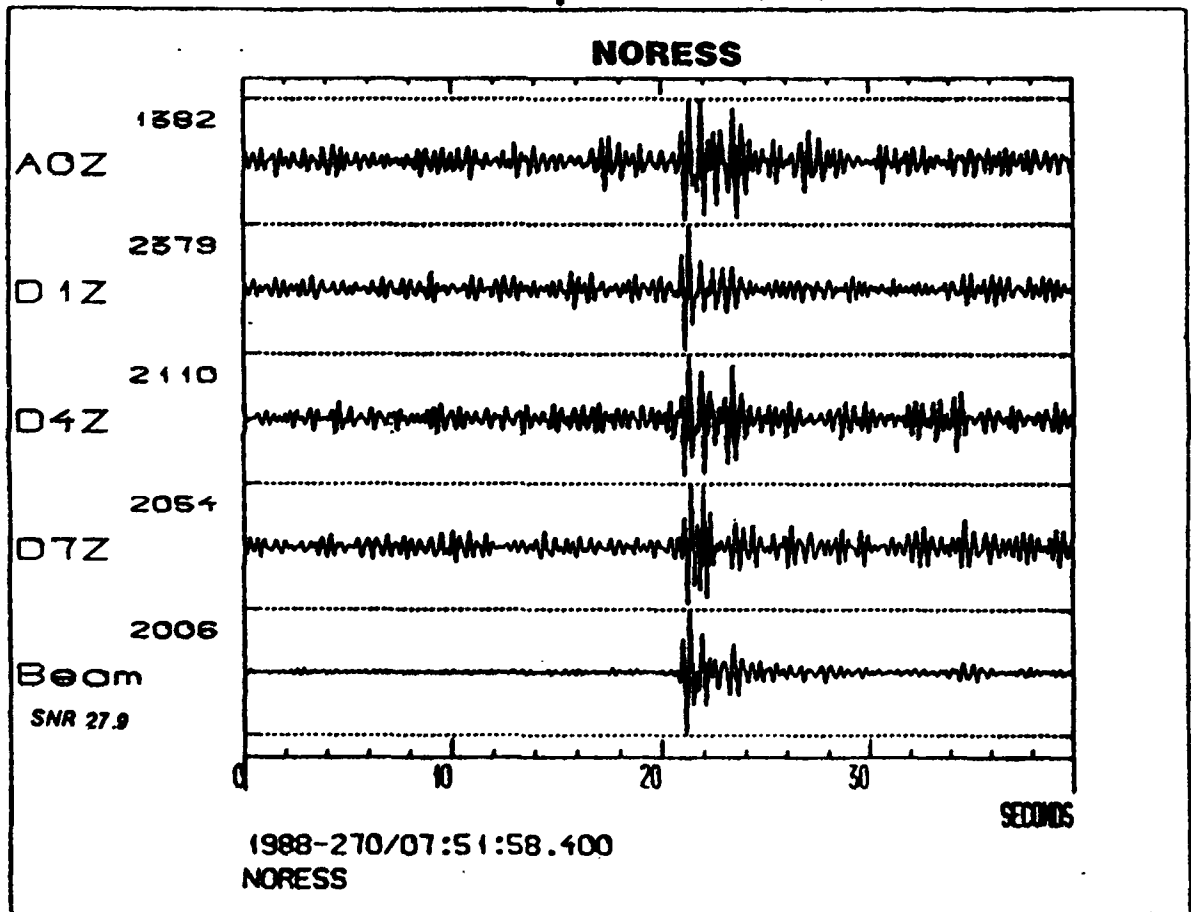


FIGURE 10

**Sempalatinsk 9/26/88**



**FIGURE 11**

### Z Component RMS Lg Comparison

S=1.04 I= -1.10 S.D.= 0.026 N= 6

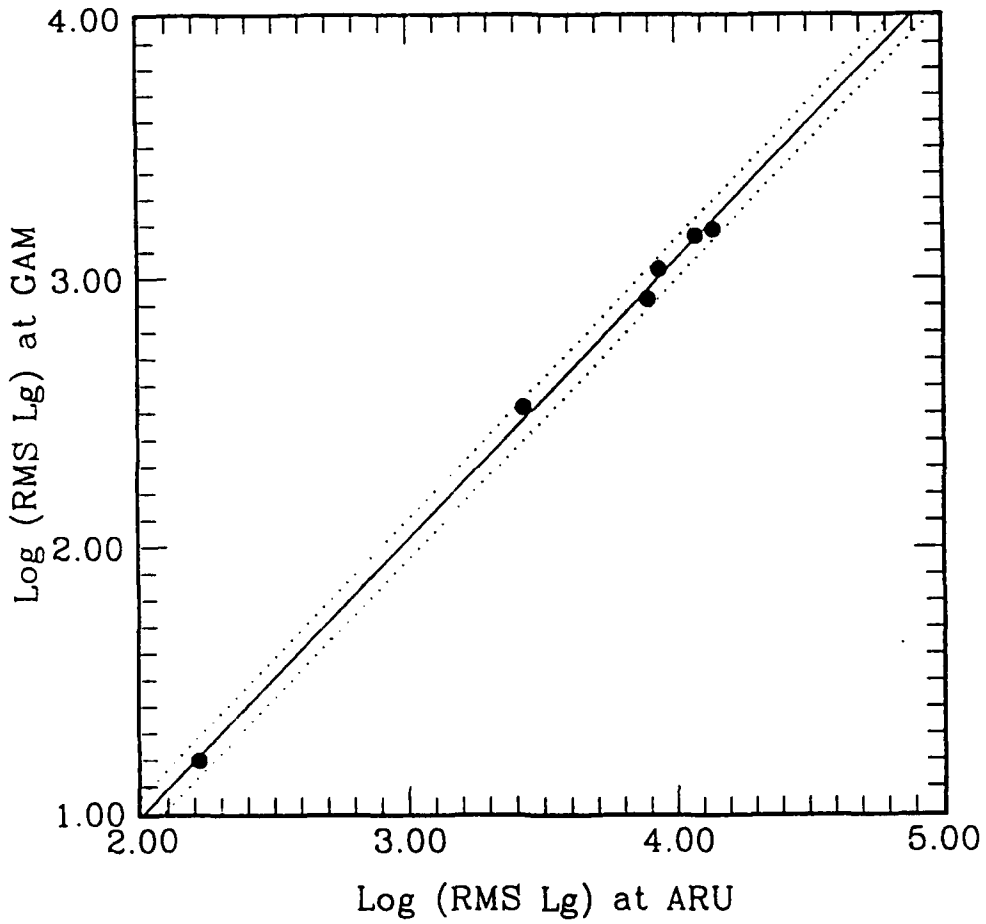


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