Calibration of Local Magnitude Scales For Use in Seismic Monitoring

J. R. Murphy, M. E. Marshall, B. W. Barker, T. J. Bennett, W. Rivers* and L. Grant*
Maxwell Laboratories, Inc., S-CUBED Division
11800 Sunrise Valley Dr., Suite 1212
Reston, Virginia 22091
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Abstract
In situations where cavity decoupling is a plausible evasion scenario, comprehensive monitoring of any eventual CTBT will require the routine identification of many small seismic events with magnitudes in the range $2.0 < m_b < 3.5$. Thus, an important issue in the assessment of monitoring requirements concerns the definition of the numbers and types of events which will generate seismic signals in this magnitude range. This has proved to be a difficult question to answer with any real degree of confidence, because the magnitude values reported for most small events are based on a variety of regional magnitude scales which may not be consistent with the teleseismic $m_b$ magnitude scale which is used to specify seismic monitoring capability. Under this project, we are attempting to quantitatively relate such regional magnitude measures to $m_b$. This is being accomplished by theoretically scaling observed regional seismic data recorded from tamped underground nuclear tests to obtain estimates of the corresponding seismic signals to be expected from small cavity decoupled nuclear explosions at those same source locations. These synthetic data are processed to determine various local magnitude measures which can then be directly correlated with the known $m_b$ values of these synthetic explosions. This theoretical scaling procedure has now been applied to regional seismic data recorded at the Scandinavian NORESS and ARCESS arrays from tamped Soviet nuclear explosions at the Novaya Zemlya and selected PNE sites and to data recorded at IRIS stations from explosions at the Semipalatinsk and Lop Nor test sites. Results of analyses of these synthetic data indicate that, even for the well-calibrated Scandinavian arrays, regional magnitude measures can show a pronounced dependence on source location and type. For example, since regional magnitude scales are typically calibrated using data recorded from small earthquakes and mine blasts, differences between explosion and earthquake regional phase characteristics, such as the $L_g/P$ ratio, can lead to consistent bias in regional magnitude determinations for explosions. Analyses of the phase and frequency dependence of such biases are currently being conducted in an attempt to define an optimum regional magnitude measure for use in seismic monitoring.

Key Words: Seismic, Magnitude, Regional, Explosion, Cavity Decoupling

* Multimax, Inc., Landover, Maryland
Objective

A central issue in current discussions of the seismic monitoring capability required to adequately verify any eventual Comprehensive Test Ban Treaty (CTBT) concerns the definition of the threshold level of seismic event size or magnitude down to which seismic events will have to be detected and identified. It is generally agreed that the capability currently exists to unambiguously identify almost all seismic events having magnitudes characteristic of well-coupled underground nuclear explosions with yields greater than a few kilotons (i.e., $m_b \sim 4$, OTA (1988)). However, in the context of monitoring a CTBT, consideration has to be given to the requirement to characterize the much smaller signals which would be expected to result from various evasive testing practices which might be employed by a nation pursuing a clandestine nuclear weapons development program. 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 comprehensive monitoring of underground nuclear tests in the 1 to 10 kt range will necessarily involve identification analyses of small seismic events with magnitudes in the range $2.0 < m_b < 3.5$. However, since such small events are generally not recorded teleseismically, their magnitudes are typically determined using one of the many proposed regional magnitude scales ($M_L$). This constitutes a problem in that such regional magnitude measures are defined in terms of seismic phases and frequency bands which are different from those associated with the traditional teleseismic $m_b$ magnitude measure and, consequently, it is not always clear how they relate to the corresponding $m_b$ values which are used to specify seismic monitoring capability. The objective of this project has been to attempt to develop an improved quantitative understanding of the relationship between $M_L$ and $m_b$ for small underground nuclear tests. This has been accomplished through analyses of synthetic data obtained by theoretically scaling observed regional seismic data recorded from tamped underground nuclear tests to obtain estimates of the corresponding seismic signals to be expected from small cavity decoupled nuclear tests at those same source locations.

Research Accomplishments

The scaling procedure used to derive the synthetic regional seismic data analyzed in this study has been described in detail by Murphy and Barker (1994). In this approximation, if the elastic radius of the seismic source of the tamped
reference explosion of yield \( W_T \) is denoted as \( \text{rel}_2 \), then the elastic radius for the corresponding cavity decoupled explosion is

\[
\text{rel}_1 = \frac{\text{rel}_2}{(DF)^{1/3}}
\]

where \( DF \) denotes the decoupling factor for a particular yield/cavity volume ratio. For each selected tamped explosion we have considered a range of decoupling factors which increase incrementally by factors of 2 such that \( DF = 2, 4, 8, \ldots, 70 \) \( W_T \) where 70 \( W_T \) corresponds to the case of 1 kt fully decoupled with a low frequency decoupling factor of 70. Now, for values of \( W_T < 100 \) kt, the corner frequency of the tamped explosion source generally lies above 1 Hz and, consequently, the \( m_b \) values corresponding to such a sequence of partially decoupled synthetic explosions can be approximated simply as

\[
m_{bi} = m_b(T) - \log (2, 4, 8, \ldots, 70 \ W_T)
\]

where \( m_b(T) \) is the observed \( m_b \) value of the tamped explosion with yield \( W_T \). A typical sequence of such source spectrum scaling operators is shown in Figure 1 for the Soviet JVE event, where a nominal seismic yield of about 115 kt has been used for that explosion. It can be seen from this figure that the scaling is strongly frequency dependent over this regional band extending from 0.1 to 20 Hz, particularly for the operators corresponding to the lower yield decoupled explosions. Not surprisingly, such frequency dependent scaling can have some pronounced effects on the characteristics of the corresponding broadband regional seismograms. This is illustrated in Figure 2 which shows the results of scaling the IRIS station GARM recording of the Soviet JVE \( (\Delta = 1380 \) km) using the range of source scaling operators from Figure 1. It can be seen that in this case the lower frequency \( L_g \) and \( R_g \) signals are progressively attenuated with respect to the higher frequency \( P \) signals as the data are scaled to lower \( m_b \) values. Clearly, such large variations in relative phase amplitudes can be expected to have pronounced effects on at least some regional magnitude measures.

The sample of tamped underground nuclear explosions for which regional seismic data were scaled using the above procedures is summarized in Table 1. It can be seen that the first two events in Table 1 were recorded at the ARPA array stations ARCESS and NORESS in Scandinavia, for which extensive magnitude calibration studies have been carried out, leading to a regional magnitude measure which is expressed as a weighted average of individual phase magnitudes determined from measured amplitudes of the \( P_n, P_g, S_n \) and \( L_g \) arrivals (Bache et al., 1991). The individual phase magnitudes for the scaled

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Novaya Zemlya 10/24/90 explosion recordings at ARCESS determined using these algorithms are plotted as functions of \( m_b \) in Figure 3 where the corresponding \( M_L = m_b \) nominal relations are also shown for reference purposes. It can be seen that these individual phase magnitude values show some significant divergences from the expected \( M_L = m_b \) relations, with the \( P_n \) and \( S_n \) values biased high by about 0.6 magnitude units and the \( L_g \) values biased low by about 0.4 magnitude units for the smaller events. This broad scatter is presumably due to the fact that the propagation path from Novaya Zemlya to ARCESS is quite different from those of the regional earthquakes and mine blasts used to calibrate the ARCESS magnitude determination algorithms. This example graphically illustrates the fact that, even for well calibrated stations, significant biases can occur for events in locations not represented in the calibration database. Another notable feature illustrated by Figure 3 is the tendency for the explosion \( L_g \) magnitudes to be lower than those determined from the other phases. This has been found to be a consistent result of the study, even for well calibrated propagation paths. This fact is illustrated in Figure 4 which shows the various magnitude measures determined from the scaled recordings of Table 1, evaluated at a fixed \( m_b \) value of 3.0. Note from the left panel of this figure that the \( L_g \) magnitude is lower than the others, even for the well calibrated PNE to NORESS path. It seems likely that this consistent bias is due to differences in the relative phase excitation levels associated with the different source types. That is, since the magnitude determination algorithms are generally calibrated using earthquake and mine blast data, it can be expected that the \( L_g \) magnitudes will be biased low for explosion sources due to characteristic differences in the average \( L_g/P \) amplitude ratios for these different source types. The right hand panel of Figure 4 illustrates the range of variation in regional phase characteristics for explosions recorded along selected paths in Central Asia. In these examples, the individual

### Table 1

<table>
<thead>
<tr>
<th>Event</th>
<th>Station</th>
<th>Estimated Yield, kt</th>
<th>( \Delta, ) km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novaya Zemlya 10/24/90</td>
<td>ARCESS</td>
<td>65</td>
<td>1110</td>
</tr>
<tr>
<td>PNE (Archangel) 7/18/85</td>
<td>NORESS</td>
<td>8.5</td>
<td>1564</td>
</tr>
<tr>
<td>Soviet JVE 9/14/88</td>
<td>WMQ</td>
<td>115</td>
<td>950</td>
</tr>
<tr>
<td>Soviet JVE 9/14/88</td>
<td>GARM</td>
<td>115</td>
<td>1380</td>
</tr>
<tr>
<td>Soviet JVE 9/14/88</td>
<td>ARU</td>
<td>115</td>
<td>1530</td>
</tr>
<tr>
<td>Lop Nor 8/16/90</td>
<td>GARM</td>
<td>215</td>
<td>1590</td>
</tr>
</tbody>
</table>
phase magnitudes were again estimated using the Scandinavian algorithms to
provide a constant reference base and, consequently, it can be expected that
careful path calibration studies could be expected to significantly reduce the
variability displayed here. However, these results do serve to emphasize once
again the very strong dependence of regional phase characteristics on the
properties of the propagation paths. Analyses of the phase and frequency
dependence of such biases are continuing in an attempt to define a more optimal
regional magnitude measure for use in seismic monitoring.

Conclusions and Recommendations

The definition of meaningful magnitude measures for small seismic events
remains as a major unsolved issue affecting assessments of CTBT monitoring
requirements. That is, since such events are not expected to be detected
teleseismically, their magnitudes will have to be estimated from regional
recordings using seismic phases and frequency bands which are different from
those employed in the teleseismic mb scale which is generally used to specify
seismic monitoring capability. In this study, we have attempted to quantitatively
relate these different magnitude measures by theoretically scaling regional
seismic data observed from tamped underground nuclear explosions to obtain
improved estimates of the corresponding signals to be expected from low yield
cavity decoupled explosions at a variety of different source locations. Analyses
of these synthetic data have indicated that, even for well calibrated stations such
as the ARPA Scandinavian arrays, traditional regional magnitude measures can
show a pronounced dependence on source type and location. In particular, it has
been demonstrated that differences between explosion and earthquake regional
phase characteristics, such as the average Lg/P ratio, can lead to consistent biases
between regional magnitude estimates for explosions and earthquakes having
comparable mb values. Such biases and associated uncertainties should be
carefully considered in the definition of required magnitude monitoring
thresholds for any eventual CTBT.

References

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Figure 1. Frequency dependent source scaling operators used to theoretically scale observed regional recordings from the Soviet JVE to simulate the signals expected from various cavity decoupling scenarios.
Figure 2. Synthetic cavity decoupled regional seismograms obtained by applying the theoretical source scaling operators of Figure 1 to the IRIS station GARM (Δ = 1380 km) recording of the Soviet JVE.
Figure 3. Regional seismic magnitudes as functions of $m_b$ derived from source scaled versions of the ARCESS recording of the Novaya Zemlya nuclear explosion of 10/24/90.
Figure 4. Variations of regional seismic magnitude measures for $m_b = 3.0$ explosions in Scandinavia (left) and Central Asia (right).