REGIONAL *P* CODA FOR STABLE ESTIMATES OF BODY WAVE MAGNITUDE: EXTENDING THE M_S:m_b DISCRIMINANT TO SMALLER EVENTS

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Sponsored by the Air Force Research Laboratory

Contract No. FA8718-06-C-0027

ABSTRACT

The most successful teleseismic discriminant is M_s:m_b, and many studies are underway to try to extend surface wave magnitude (M_s) estimation to regional distances. A problem that is encountered at regional distances and small magnitudes is how to estimate m_b so that the M_s:m_b discriminant is meaningful and consistent with teleseismic measures.

Over the past several years, a regional *S*-coda wave methodology has been developed that provides for the lowest variance estimate of the seismic source spectrum. Thus, regional M_W and m_b estimates derived from *Sn* and *Lg* coda are very stable, even when only a single station is used. However, these m_b*'s* are inherently biased for earthquakes because they are an *S*-based measurement, and explosions are relatively depleted in *S*-waves. Previous research projects have used region-specific m_b scales based on direct measurements of *Pn* and *Pg* to improve the M_s:m_b discrimination, even though the m_b estimates often had a large variance.

In our preliminary research, we have found that *P*-coda envelopes for both explosions and earthquakes can be obtained for events from both the Nevada Test Site (NTS) and Novaya Zemlya (NZ) regions without bias. Our next step at NTS will be to derive path corrections, similar to the approach of Mayeda et al. (2003) for *Lg*-coda. We will compare inter-station scatter of distance-corrected amplitudes as a function of window length. This will provide an empirical measure of error based on window length for each frequency band. For each frequency band, we will regress our coda envelope amplitudes against regional and teleseismic estimates of m_b (e.g., m_b(*Pn*), m_b(*P*)) to determine which band provides the lowest variance. This will yield slope and intercept values for each frequency band. We will then derive m_b(*Pn*) and m_b(*P*) (following Denny et al., 1989) to compare against m_b(*P*-coda) to assess performance at the network and single-station level. Most of the nuclear explosions already have an m_b(*Pn*) compiled by Vergino and Mensing (1989). Patton (2001) has estimated m_b(*Pn*) for many historic NTS earthquakes. For recently recorded earthquakes, we will need to estimate m_b(*Pn*) and m_b(*P*). Finally, we will compute M_s(VMAX) from the regional stations and form an M_s(VMAX):m_b(*P*-coda) discriminant to compare against teleseismic values and trends.

OBJECTIVE

An important aspect of nuclear explosion monitoring is discrimination and yield estimation. U.S. monitoring scientists must be able to both discriminate explosions from earthquakes as well as assign an accurate lower bound to the yields for nuclear explosions detonated in regions of monitoring concern. Seismic monitoring has historically been performed on large (> ~1 kt) nuclear explosions, which typically have dozens of teleseismic *P*-wave recordings (e.g., Murphy et al., 2001). The large number of measurements can be used to effectively average over the three-dimensional (3D) Earth structure and any azimuth-dependent effects from the source. In some special cases t* corrections have been performed to account for potential upper mantle structure (e.g., $m_b(P)$ bias for NZ explosions).

Over the past several years, the Department of Energy (DOE) labs, have developed a regional coda wave methodology to obtain the lowest variance estimate of the seismic source spectrum. Thus, regional M_W and m_b estimates derived from *Sn* and *Lg* coda are very stable, even when only a single station is used. However, these m_b*'s* are inherently biased for earthquakes because they are an *S*-based measurement, and explosions are relatively depleted in *S*-waves. Previous research projects have used region-specific m_b scales based on direct measurements of *Pn* and *Pg* to improve the $M_s{:}m_b$ discrimination, even though the m_b estimates often had a large variance.

This project addresses a number of questions. Can we reduce the variance in regional m_b estimates using a sparse-station *P*-coda methodology, as opposed to using multitudes of direct *Pn* and *Pg* measurements? How will the stability of these m_b(*P*-coda) estimates compare to the highly successful and stable (but unfortunately biased) methods involving *Lg* and *Sn* coda? How many stations will be needed? Will the use of m_b(*P*-coda) improve $M_S{:}m_b$ discrimination at regional distances? Research conducted during the past year has answered several of these questions as described in the following sections of this paper.

RESEARCH ACCOMPLISHED

Underground nuclear explosion monitoring requires the discrimination of small nuclear explosions and earthquakes. The most successful teleseismic discriminant compares the 20-second period surface wave magnitude (M_s) with the ~1-Hz body wave magnitude (m_b). This discriminant is referred to as $M_s{:}m_b$, and many studies are underway to try to extend surface wave magnitude (M_s) estimation to regional distances. A problem that is encountered at regional distances (<~2000 km) and small magnitudes is how to estimate m_b so that the $M_s{:}m_b$ discriminant is meaningful and consistent with teleseismic measures.

Novya Zemlya. We measured relative *P*-coda envelope amplitudes using the October 24, 1990, NZ explosion as a reference event. By scaling narrowband envelopes between our reference event and the other explosions and earthquakes, we were able to tabulate relative coda amplitudes. Figure 1 shows coda envelopes at the Norwegian Seismic Array along with derived body wave magnitudes made from the *P*-coda. These preliminary results are very promising in that earthquake m_b's are also in good agreement with the maximum likelihood magnitude, m_b(ML). This is in sharp contrast to results from regional $m_b(Lg)$ and m_b(*Lg* coda) (e.g., Patton, 1988; Mayeda 1993). In those studies, m_b was tied to explosions at the NTS; however, applying the same formulas to earthquakes results in an overestimation of ~1 magnitude unit. For example the 1992 M_W 5.5 Little Skull Mountain earthquake at NTS would have an $m_b(Lg)$ of ~6.6.

Paths from NZ to the Norwegian Seismic Array are still at regional distance and one might expect the *P*-wave and its coda to be comprised of waves that sample the crust and upper mantle over a range of take-off angles from the source. At teleseismic distances however, we might expect that the averaging nature observed for local and regional coda waves to breakdown. At these distances, first arriving *P*-waves are likely emanating from a limited range of take-off angles near the bottom of the focal sphere. To investigate this, we processed roughly 30 NZ explosions recorded at the U.K. arrays Eskdalmuir in Scotland (EKA) and Yellowknife in Canada (YKA), located at ~30 and 44 degrees from NZ, respectively.

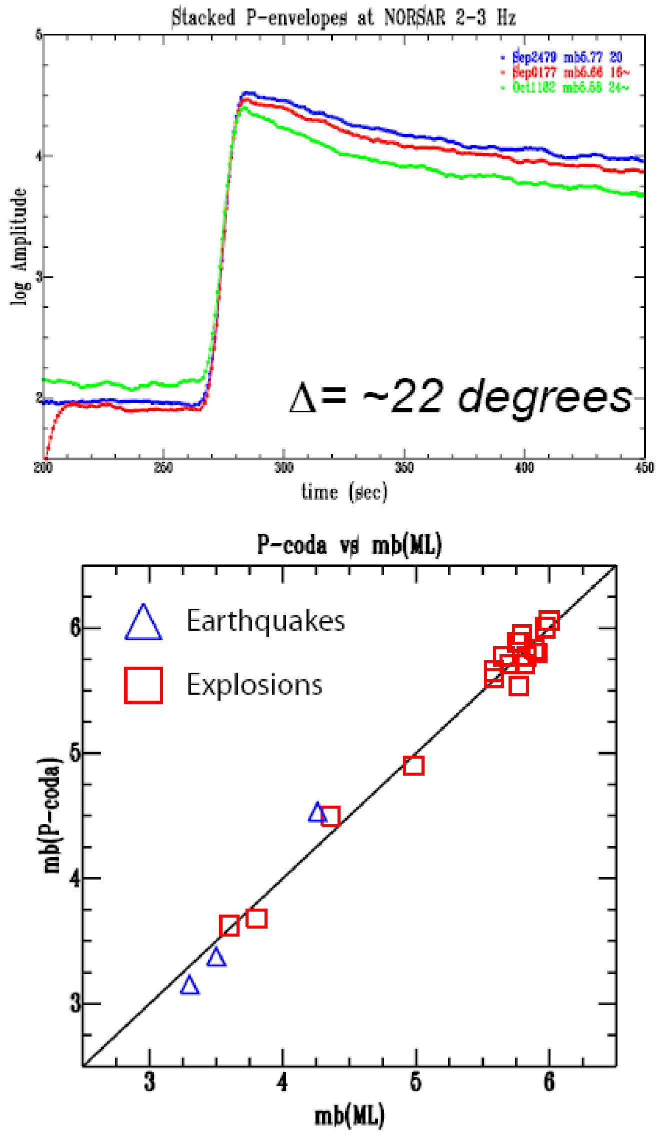

Figure 1. *P*-coda envelopes (2–3 Hz) stacked over the Norwegian Seismic Array for three NZ (top). The m_b(*P*-coda) for both explosions and earthquakes (bottom) do not exhibit a bias, in contrast to m_b(Lg) and m_b(Lg coda).

Figure 2 shows envelopes at EKA for 4 NZ explosions with roughly the same magnitude that were located within a few kilometers of each other (see Figure 1 in Lilwall and Marshall, 1986). We see an immediate discrepancy for the September 24, 1979, event. Though it has the largest m_b(ML) it is roughly a factor of 3 smaller in amplitude (0.5 in $\log_{10}$) at EKA relative to the other three events. The direct *P*-wave, coda, and *PcP* phase (not shown) are all small. In fact, the EKA station magnitude for this event is also low relative to the global m_b(ML) estimate. The closest event is the September 27, 1978, event, but this does not appear to be anomalous. Careful inspection of the raw data shows nothing unusual for the September 24th event. (Note: The pre-event noise is lower for the October 11, 1982, event because of improvements to the electronics in late 1979). We note that this event at the Norgwegian Seismic Array is in good agreement with the m_b(ML) as well as at YKA. Assuming this is real, then this suggests a near-source process such as focusing directly beneath this event. Moreover, the scale-length must be small since a nearby event is not affected. This supports the notion that teleseismic *P*-codas will not have the same averaging properties that local and regional codas exhibit.

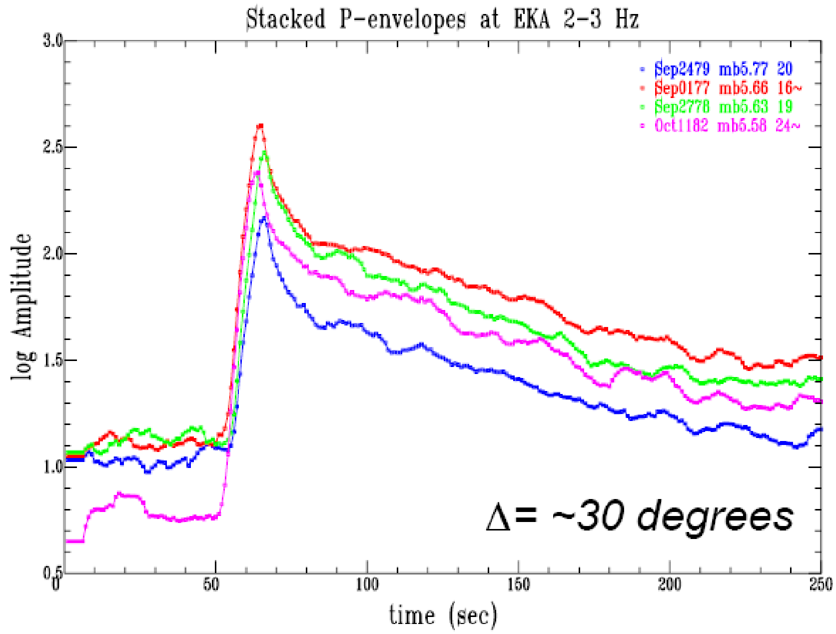

Figure 2. We show 4 NZ explosion *P*-coda envelopes at station EKA for events with roughly the same magnitude; however, we observe a large discrepancy with the September 24, 1979, event. Though it has the largest magnitude, it is a factor of 3 smaller in amplitude.

Nevada Test Site. Next, we applied the same methodology to explosions and earthquakes at NTS. Using the April 18, 1983, explosion as a reference, we computed m_b(*P*-coda) at the Berkeley seismic station, BKS, located ~5.5 degrees away. This amounted to roughly 60 seconds of *Pg* coda that we were able to measure. As found for NZ events, we also did not find any bias between m_b(*P*-coda) for explosions and earthquakes relative to the teleseismic m_b(*P*).

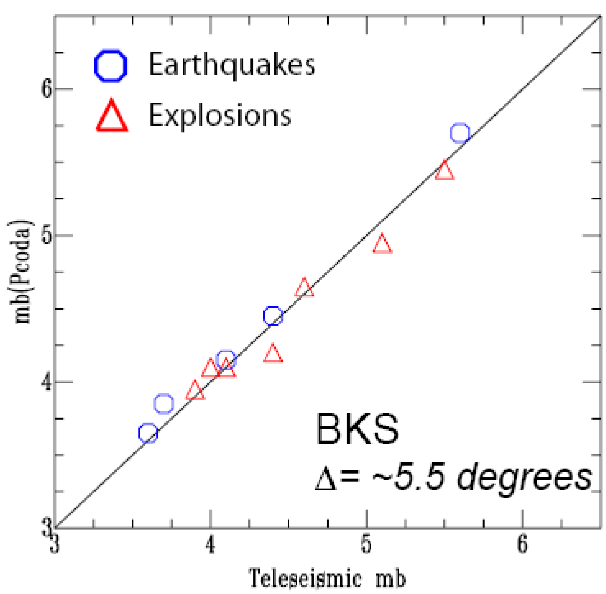

Figure 3. Relative *P*-coda envelope amplitudes were made using the August 18, 1983, explosion as a reference. m_b(*P*-coda) for NTS explosions and earthquakes agree with teleseismic m_b(*P*), in good agreement with Norwegian Seismic Station results for NZ events. At 5.5° degrees, we had ~60 seconds of *P*-coda to form the measurements on multiple narrow frequency bands that were regressed separately.

CONCLUSIONS AND RECOMMENDATIONS

Our preliminary findings suggest that at regional distances the *P*-coda can be used as a surrogate for teleseismic m_b for both earthquakes and explosions, based on the findings at the Norwegian Seismic Station for NZ events as well as those at NTS (e.g., Figures 1 and 3). At teleseismic distances, the *P*-coda appears to share the same radiation pattern as the direct *P*-wave and does not appear to average over the focal sphere as is observed for local and regional shear waves (e.g., Figure 2). Nonetheless, the derived body wave magnitude m_b(*P*-coda) at EKA and YKA for NZ explosions is in good agreement with the globally averaged results using direct teleseismic *P*. Furthermore, m_b(*P*-coda) can be computed on clipped data which is quite common for the larger NZ explosions recorded at EKA and YKA.

In addition to computing m_b(*P-coda*) vs M_s(VMAX) for both datasets, our plans are to process many regional and near-teleseismic stations that recorded NTS events at a range of azimuths. We will process many regional and near-teleseismic stations that recorded TS events at a range of azimuths. Specifically, we will

1. document the inter-station stability and compare the direct *P* results,
2. document the magnitude variance as a function of the coda measurement window,
3. develop magnitude-yield curves,
4. derive detection threshold curves,
5. evaluate the transportability of foreign test sties, and
6. generalize the method to broad area monitoring as is done with the regional shear-wave coda methodology.

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