REGIONAL MAGNITUDE RESEARCH SUPPORTING BROAD-AREA MONITORING OF SMALL SEISMIC EVENTS

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ABSTRACT

Los Alamos National Laboratory has a long-standing magnitude research project in support of regional yield estimation and source discrimination. In recent years, this project has developed magnitude-yield scaling relationships based on regional P and S phases and coda waves to improve capabilities to monitor nuclear explosions over broad areas and at low yields. Essential to this development is a better understanding of the transportability of scaling relationships for explosions conducted in different media and for regional phase propagation through different geologic structures. Due to the great variability of regional seismograms, the methods developed for broad-area monitoring must be adaptable to different phases and different frequency bands. These requirements pose a significant challenge from a practical standpoint and from the standpoint of an underlying physical model, which any broad-area method must have to be ultimately successful.

A significant finding of our past research is that the scaling is not the same for magnitudes based on P and S waves. This finding has been documented extensively in previous papers and Seismic Research Review (SRR) presentations for 1 Hz magnitudes showing that mb(P) and mb(Pn) scale at higher rates with yield than do mb(Lg) and the logarithm of apparent Lg coda source amplitudes (ACSA). We have also found that the scaling slopes of mb(Lg) and log (ACSA) are identical, supporting claims of a common source mechanism(s) of Lg and Lg coda waves from explosions. These results have important implications for yield estimation and discrimination, as well as our understanding of S wave generation mechanisms for explosions. The latest observations will be summarized in this paper on plots of one amplitude measure versus another (e.g., mb(Pn) versus log (ACSA), etc.) for test sites around the world. Comparisons for Nevada Test Site (NTS) explosions provide evidence that coupling effects cancel on such plots leaving behind clear indications of scaling differences.

In the past few years, our research has started to characterize the scaling behaviors of regional phases across frequency bands of interest for broad-area monitoring. These include bands both higher and lower than 1 Hz, and phases Pn, Lg and their associated codas. Log (ACSA) for 1.5-2.0 and 2.0-3.0 Hz bands show scaling rates as low as the results for 1 Hz if not lower. In this paper we present our latest observations of multi-band scaling observations for regional P and S waves. These observations are complimented by coda source spectra which display spectral peaking unlike earthquake spectra. This work is forming the observational basis from which to draw insights for improving yield-estimation and discrimination methodologies and for establishing a physical model to support these monitoring functions.

OBJECTIVE

We seek to improve yield estimation and seismic discrimination capabilities for broad areas and small events through the development of regional magnitude methodologies and data sets for direct phases and coda waves. One way our research advances the state of the art in nuclear explosion monitoring is to characterize the scaling behavior and transportability of regional magnitudes based on path-corrected amplitudes using advanced calibration techniques.

RESEARCH ACCOMPLISHED

In recent years, we have witnessed exciting technical advances showing great promise to increase the precision of seismic yield estimates and extend Ms-mb discrimination to small magnitudes through the use of amplitudes measured off regional seismograms. With these advances has come an extraordinary change in the measurements we rely upon since they are often based on the amplitudes of shear phases (Lg, Sn) and codas following those phases, and to a lesser degree on the compressional phases that explosions excite with great efficiency. This is because shear phases are usually the largest on regional seismograms and hence are the best recorded as source sizes decrease and noise levels increase, an important consideration for the ability to do low-yield monitoring. The reliance upon regional shear phases represents a paradigm change from the way seismologists monitor nuclear explosions at teleseismic distances, and this change is a driver for much new innovative research in our community today.

A significant component of the research in this project is directed at characterizing the scaling behavior of regional magnitudes over a broad yield range and in different frequency bands in order to address the challenges confronted by monitoring small events in broad areas. Much of this work is focused on coda waves following Lg, and in the process, we are forming an observational basis from which to draw new insights for improving yield estimation and extending Ms-mb to smaller magnitudes. Equally important is the need to develop a physical model for shear-wave generation by underground explosions and to lay a theoretical foundation supporting the empirical methods employed for regional monitoring. These scaling observations provide important constraints that future models must satisfy.

The ability to estimate yields and discriminate seismic events especially at small magnitudes depends in large part on the energy partitioning between P and S phases and the manner in which the phases scale with yield or source size (e.g., the yield or magnitude dependence of energy partitioning). Another important consideration is the portability of seismic measurements across broad areas, as scatter between areas could be a sign that path effects are not being completely corrected for in our measurements or it could be a sign of intrinsic source effects. This is one reason that so much research has been invested in the calibration of regional path effects, and the development of tomographic models for 1- and 2-D path corrections. In many areas of monitoring concern, these models are nearing a maturity where we are confident that the path effects are effectively and completely removed. We believed this to be so for the corrected amplitudes used to measure magnitudes in this study.

In our project, much effort has been spent on developing methodologies to estimate regional magnitudes and building magnitude data bases of historic explosions in Asia, as well as at the Nevada Test Site (NTS) where so much ground truth information is known. Over the years, our efforts, joint with Livermore's, have investigated coda amplitudes of Lg and Sn waves, tied to seismic moment through an innovative calibration method (Mayeda and Walter, 1996), for purposes of yield estimation, and the results of this work have shown great promise. The corrected coda measurements are referred to as "apparent coda source amplitudes" (ACSA) with units of Nm, and they are measured through a bank of narrowband filters with set bandwidths, the most extensively studied so far being 1.0-1.5, 1.5-2.0, and 2.0-3.0 Hz bands. More bands exist at frequencies below and above these, but to date we have been able to develop yield scaling relationships for these three bands and to study some aspects of their transportability.

A remarkable finding in the results for Lg and Sn 1.0-1.5 Hz ACSA is a difference in scaling compared to teleseismic mb(P), where 1 Hz P wave amplitudes appear to scale with yield at a faster rate than coda amplitudes of Lg and Sn waves. Similar differences have been noted for mb(Lg) and mb(Pn) observations of NTS explosions for the traditional 1 Hz short-period passband defined by the World-Wide Standard Seismographic Network response (WWSSN) (Patton, 2000). In this paper, we will review some of these observations and discuss their implications for the source and our ability to estimate yield and discriminate seismic events. This work is ongoing, and we are currently extending our investigations to other frequency bands and a broader range of yields by incorporating new observations for small explosions.

Here we show a series of scaling results plotting the seismic magnitude of one wave type against the magnitude of another. This has the benefit of reducing many effects related to source coupling, as the first illustration shows. Figure 1 is a plot of mb(Pn) against teleseismic mb(P) for NTS explosions fired on Yucca Flats and in Rainier Mesa. Yucca Flats explosions were detonated in dry and water-saturated tuffs and in dry alluvium. Rainier Mesa explosions exhibit coupling variables due to perched water tables, and explosions in dry alluvium generally couple poorly due to their low material strength. Nevertheless, the scatter plot shows that all observations plot uniformly around the line of equality. This is due to the fact that coupling variations caused by gas porosity and material strength cause near-equal perturbations to the amplitudes of P and Pn waves. Thus, such perturbations tend to move the data points in Figure 1 on trajectories parallel to a line of unit slope. Other effects must be the cause of the scatter, and background seismic noise is a likely candidate judging from the increasing scatter at small magnitudes. The amplitudes of Pn waves are often small, and teleseismic P are difficult to record for small explosions at such great distances. Thus, there are strong practical reasons for using regional shear phases to monitor at small magnitudes.

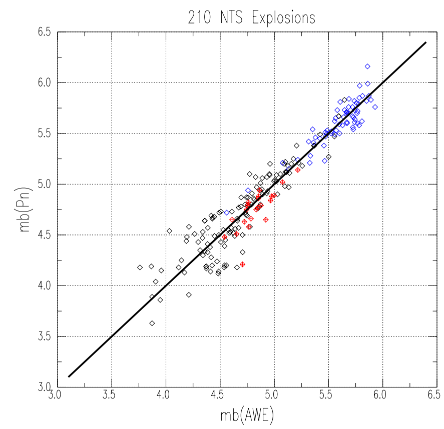

Figure 1. Regional mb(Pn) versus teleseismic mb(P) reported by Blacknest, Atomic Weapons Establishment (AWE). Blue, Yucca below water table; black, Yucca above; red, Rainier Mesa.

The next scaling plots compare mb(Lg) with log(ACSA) for Lg coda wave amplitudes in the 1.0-1.5 Hz band. Figure 2a is a plot of NTS explosions, and Figure 2b is for explosions at the Kazakhstan Test Site (KTS) at Semipalatinsk. KTS observations utilized waveforms from the Borovoye archive (Kim *et al*., 2000), as well as waveforms of regional stations for explosions in the late 80's. We include three 25-ton chemical explosions from the 1997 Depth of Burial (DOB) experiment in Figure 2b, and other chemical explosions will be included on future plots to better characterize the scaling at small yields. Note that Degelen explosions were conducted in tunnels as were Rainier Mesa explosions, while shots at Balapan and on Yucca Flats are in vertical shafts.

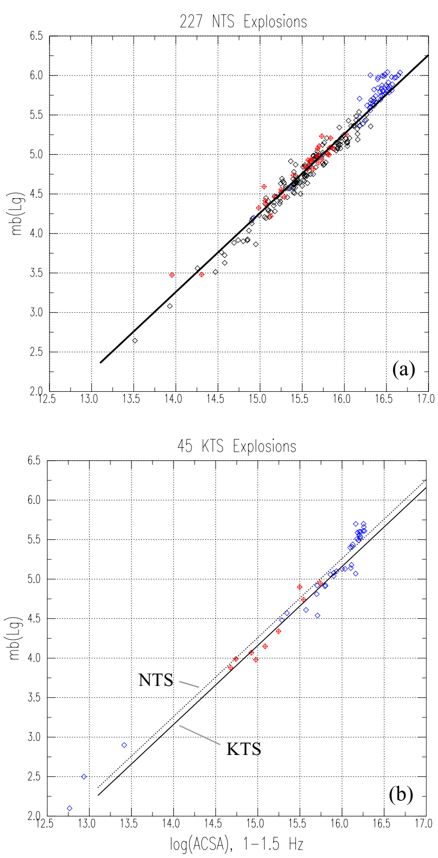

Figure 2. mb(Lg) versus log(ACSA) based on Lg coda waves. Color coding for NTS explosions is the same as in Figure 1. For KTS, blue are explosions at Balapan, while red are Degelen Mountain shots.

It may not come as a complete surprise that the scaling of log(ACSA) for Lg coda waves is very similar to the scaling of mb(Lg) judging from the good agreement of the observations with scaling relationships for a unit slope (lines in Figure 2). This suggests that the generation mechanisms of S waves by explosions are common to both Lg and Lg coda waves (also for Sn waves, as indicated by other results). There is a sign at large yields that the observations bend upward as if log(ACSA) is saturating before mb(Lg). This appears to be a bandwidth issue since Lg amplitudes were measured through a WWSSN short period response characterized by gradual frequency roll-offs, while the narrowband filters used for coda measurements have rapid fall-offs on both shoulders of the response (two-pass Butterworth filter with four poles, i.e., 48 db/octave). Thus the Butterworth filters cut off energy at both high and low frequencies before the WWSSN response does. This illustrates the care with which comparisons should be made for observations taken with different frequency responses, and in subsequent plots, we avoid comparisons at large magnitudes.

Coupling variations are also mitigated on the plots in Figure 2 for the same reasons they are in Figure 1. On the other hand, the scatter is reduced considerably for Lg and Lg coda waves. This is due in part to better signal-to-noise conditions, but it should be mentioned that Lg and Lg coda observations are all based on data from the Livermore NTS Network, while the network used for teleseismic mb measurements changed station composition from event to event, and this is a source of additional scatter. It is also worth pointing out that the emplacement style, whether in tunnels or in vertical shafts, has little impact on these comparisons, both at NTS and KTS.

Of significance is the very good comparison between the scaling relationships for NTS and KTS explosions in Figure 2 (see lines plotted for NTS and KTS in Figure 2b). This suggests two rather important findings. First is the effectiveness of our path calibrations for correcting Lg and Lg coda wave amplitudes in regions of contrasting geologies, one characterized by the extensional tectonics of the Basin and Range in western U. S. and the other by the continental collision of southern Asia and compressive tectonics. The second finding reinforces our conclusion about the commonality of Lg and Lg coda-wave source generation for NTS and KTS explosions. Thus it appears that the amplitude perturbations caused by S-wave mechanisms are of the same strength for Lg and Lg coda so that the trajectories of data points on our plots are parallel to a line of unit slope, just as they are for coupling perturbations. This finding does not provide any information about the size of the perturbations at the respective test sites, which is of importance for transportability. Information about the size is inferred from the next set of scaling plots.

Figure 3 shows regional and teleseismic mb plotted against log(ACSA) for NTS and KTS explosions. At this stage in our research we have far more observations for NTS (274 combined mb(P) and mb(Pn) measurements), but more measurements for Asian explosions will be available in the near future to better resolve the scaling behavior. At the present time, our KTS data set numbers 89 explosions including three chemical shots, two from the Omega series in the tunnels of Degelen Mountain and one from the DOB experiment. All of these chemical explosions were uncontained bursts with significant cratering effects. Such phenomenology introduces a degree of uncertainty into our interpretations of the scaling relationships, as does the scatter of observations for nuclear explosions at Degelen.

Amplitude scaling differences between mb(P) and log(ACSA) for Lg coda waves are apparent in the NTS observations. The slope of the line plotted in Figure 3a indicates P amplitudes scale 13% faster than Lg coda amplitudes in log space, consistent with the scaling results of mb(Pn) and mb(Lg) (Patton, 2000). It is important to note that the difference in amplitude scaling is not a reflection of the actual difference in yield scaling for P and Lg coda waves because containment practices will also introduce systematics affecting the amplitude scaling. Our investigations of NTS explosions have shown that log(ACSA) decrease with depth of burial, a surrogate for yield, at roughly twice the rate of P log amplitudes. This will tend to reduce the slope of the data as plotted in Figure 3. Such effects further highlights our concern with the KTS observations, since the chemicals were underburied, a rare occurrence at NTS, and the nuclear explosions were conducted by the former Soviet Union with containment practices that differed considerably from those followed by the U. S..

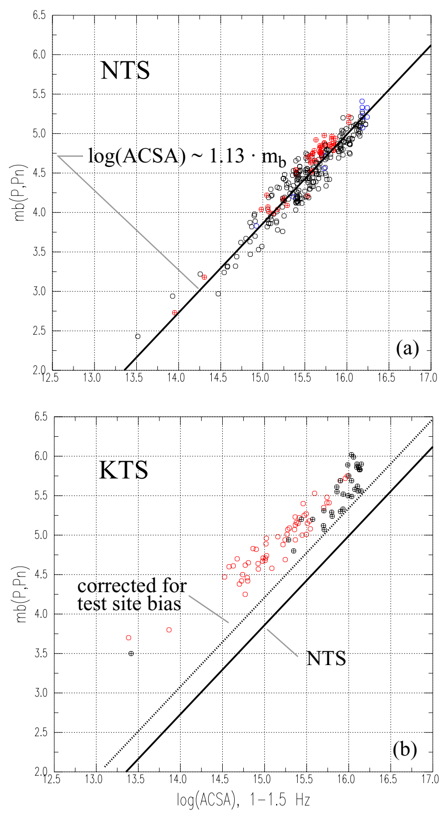

Figure 3. mb(P), mb(Pn) versus log(ACSA) based on Lg coda waves. Color coding is the same as in Figures 1&2. No relationship is shown for KTS shots due to limited observations at small yields.

One significant result in Figure 3 is the large offset between the NTS and KTS observations. This offset is not about to change with the addition of new observations at small yields that we are currently working on. The effectiveness of path corrections for log(ACSA) measurements was already noted above in regard to Figure 2b, where the good agreement between NTS and KTS scaling results implies that path effects have been removed from Lg and Lg coda wave amplitudes. For mb however, it is well known that a regional bias in western U. S. reduces the teleseismic magnitude of NTS explosions by as much as 0.4 mu. This also applies to mb(Pn) since the mb(Pn) scale for western U. S. was calibrated against mb(P) observations for earthquakes and explosions (Denny et al., 1987; also note that the equality line goes directly through the magnitude observations in Figure 1). Correcting the mb observations for test site bias brings the NTS relationship into better agreement with the KTS observations, but it still does not account for the entire offset (see Figure 3b).

The effect of material properties on P-wave amplitudes is related to the factor $[1/(\rho\alpha^3)]^{0.5}$ (Stevens and Day, 1985). For nominal P velocities (α) and densities (ρ) of media at the Yucca and Balapan test areas, the relative amplitudes of P waves are predicted to be ~0.3 mu larger for NTS explosions. If corrections for this effect were made to the NTS relationship, the offset would increase, shifting the relationship downward to nearly its original position in Figure 3b. On the other hand, we argue that material effects are also present in the Lg observations, and if they are of similar size, material properties will have little net effect on the offset. In any case, an offset remains between the corrected NTS relationship and the KTS observations, and this is an indication of source and/or propagation effects yet to be accounted for in the observations. The explanation we favor is seismic wave scattering close-in to the explosion, where the scattering environment is stronger at NTS compared to KTS, and the amplitudes of S waves generated by P-to-S or Rg-to-S scattering are larger than the amplitudes generated by KTS explosions for the same yield. This is plausible in light of the contrasts in local geology and structural heterogeneity for NTS and KTS test sites. Furthermore, our path corrections will not account for these effects since the calibration data are based on earthquakes. Under this scenario, the entire offset in Figure 3b is caused by the NTS log(ACSA) observations being shifted to the right more than the KTS observations as a result of significant differences in the strength of near-field scattered wavefields at the two test sites. If this scenario is true, the implications for transportability are readily apparent.

We are also characterizing amplitude and yield scaling relations as a function of frequency. Figure 4 compares the amplitudes of 2-3 Hz log(ACSA) with those in the 1-1.5 Hz band. Observations of small chemical explosions detonated at Balapan as part of an emplacement hole closure project supported by the U. S. Department of Energy through the U. S. Defense Special Weapons Agency are plotted on this figure. Log(ACSA) in the 2-3 Hz band show signs of saturation for apparent moments greater than 10^{14} Nm. We will compare the scaling of Pn amplitudes with ACSA for Lg coda waves in different frequency bands on our poster to ascertain what these data reveal about scaling behaviors at frequencies above 1 Hz.

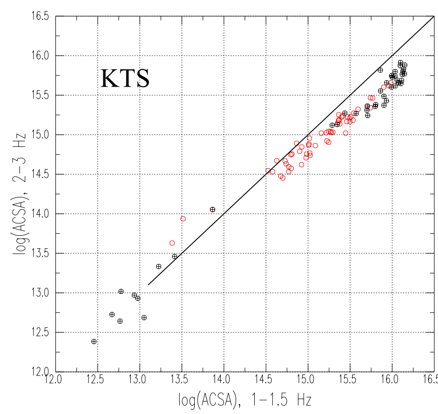

Figure 4. 2-3 Hz log(ACSA) versus 1-1.5 Hz log(ACSA). Color coding is the same as Figure 2b.

CONCLUSIONS AND RECOMMENDATIONS

The magnitude research project at Los Alamos National Laboratory is focused on improving yield estimation and seismic discrimination capabilities for broad areas and small events through the development of regional magnitude methodologies and data sets for direct phases and coda waves. A significant component of the research characterizes the scaling behavior of regional magnitudes over a broad yield range and in different frequency bands in order to address the challenges confronted by monitoring small events in broad areas. We have summarized some explosion results of this research in this paper, but much more research is needed to characterize observations in different frequency bands and for different seismic phases including coda waves.

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