INFRASOUND STUDIES FOR YIELD ESTIMATION OF HE EXPLOSIONS

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ABSTRACT

Southern Methodist University (SMU) is conducting investigations to determine the yield of high explosive (HE) explosions from infrasound signals. In particular SMU is investigating how the period and amplitude of infrasound signals scales with the yield of HE explosions. To date there has been little work on this particular topic involving small HE explosions. Our data suggests that the cube root relationship between the yield and dominant period of the signals holds to approximately 2,500 lb, while below 2,500 lb, the relationship may be rolling off towards origin. Also, the dataset collected at distances within the “Zone of Silence” appears to have a tail at higher frequencies that is related to the complexity of stratospheric signals. Tropospheric and thermospheric signals are of limited use at these ranges, and because they have different frequency content than stratospheric arrivals should be treated separately.

Analysis of a week-long experiment revealed that the amplitude of near surface tropospheric arrivals have similar rates of attenuation with distances. However, we have observed nearly one order of magnitude difference in the amplitudes, and a correction based on wind values from the local meteorological data did not reduce this scatter.

OBJECTIVES

SMU is conducting investigations to determine the yield of HE explosions from infrasound signals. In particular SMU is investigating how the period and amplitude of infrasound signals scales with the yield of HE explosions. To date there has been little work on this particular topic involving small HE explosions. Studies have been conducted by the nuclear monitoring community on nuclear and large chemical explosions ranging from less than a kiloton to tens of megatons (Armstrong [199]), Stevens et al. [2002], Pierce and Posey [1971], Clauter and Blandford [1998], Whitaker [1995], references discussed in McKisic [1997]). There were a handful of other technical reports that studied the effects of blasts, for damage assessment purposes (ANSI, 1983 and Douglas, 1987). However, these technical reports dealt mostly with the behavior of the overpressure at very short distances, and it does not address the problem of scaling at regional distances (within the so called “Zone of Silence”). Our main goal is to develop amplitude and period scaling relationship at local and regional distances, extend the relationships to greater distances and create a database of ground truth events. The ranges of the explosions that will be used in this study are from 500 kg to 60 tons of TNT equivalent, well below the previous yield ranges.

RESEARCH ACCOMPLISHED

Source

Approximately 36 km from the Nevada Seismic Array (NVAR) there is a U.S. Army demolition range (called New Bomb) where obsolete munitions are disposed of on a routine basis. Figure 1 shows the general setting area and an example of an infrasound observation at NVIAR. Usually the source is represented by a suite of several detonations spaced 30 seconds to a minute apart. The source is extremely well calibrated and we are able to obtain accurate origin times within a fraction of a second (Negraru et al., 2010). Excellent cooperation with the officials in charge of detonations allowed us to obtain weight of detonations, and we have used to it calibrate a seismic amplitude/weight for all shots (see below).

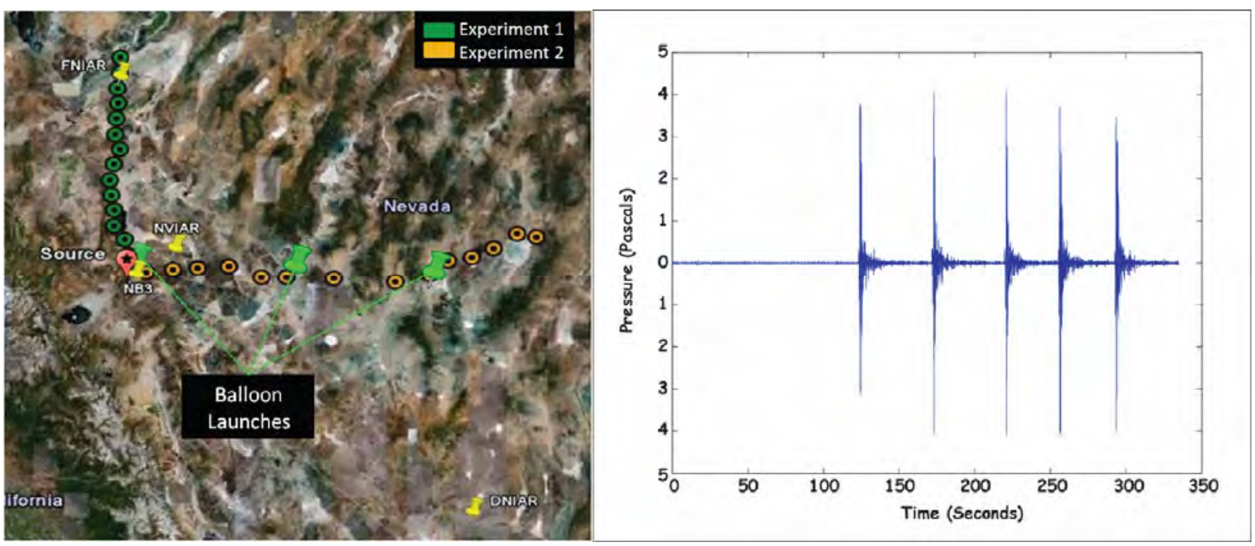

Figure 1. Google image showing the location of the study area and stations deployed (left) and a typical New Bomb detonation at NVIAR.

Data

During 2009, SMU installed two small aperture 4-element infrasound arrays to monitor the disposal activities at New Bomb. The first array was installed in June 2009 near Fallon, Nevada, approximately 154 km north of New Bomb. The second array was installed at the end of October 2009, 293 km south-east of New Bomb, near Mercury NV. The arrays were called accordingly FNIAR and DNIAR (from Desert Rock, Nevada, and the name of the NOAA weather station where the array is located). Since the first array started operating until June 2011 there were nearly 2,000 explosions at New Bomb in 250 operating days.

In addition to the data from these two arrays we also used data from two experiments carried out in June 2009 and December 2009. During these experiments we deployed a total of sixteen infrasound sensors in a line at distances from 20 to 276 km. Both deployments lasted a week. The locations of the arrays and the single stations are also shown in Figure 1. During the first experiment we placed 14 single-channel digitizers at distances ranging from 23 to 176 km (spaced about 10 km apart) north of the detonation site. The second experiment consisted of a similar deployment with instruments spaced about 20 km apart. Unfortunately, due to weather conditions, New Bomb operated only a single day in that week. Other datasets that we proposed to use in the current research project are of larger yield explosions recorded at greater distances, such as the motor rocket detonations at the Utah Test and Training Range, munitions disposal detonations in Finland and the large calibration experiments from Israel. We have started analyzing these datasets recently and they will not be discussed in detail in the current paper.

Nearly 80% of the FNIAR observations have stratospheric celerity, while about 20% of the arrivals are tropospheric. DNIAR is located much further, and we have observed three types of arrivals. Modeling using the tau-p method of (Garces, 1998 and Drob, 2010) suggests that the observed arrivals are tropospheric, stratospheric, and thermospheric. DNIAR also have strong seasonal variations and stratospheric arrivals are not always observed during summer months.

Weight Information

The weight of the disposed material is well known, but actual yield variations due to different explosivity characteristics of the material are not exactly known. The officials in charge of the disposal facility keep and provide us with detailed logs of the detonations with the weights of the material disposed. Also in part due to the very large amount of data (nearly 2,000 explosions in two years), we decided to calibrate a weight/seismic relationship. The calibrated relationship given in figure 2 is:

$$\log_{10}(\text{WEIGHT}) = \log_{10}(\text{RMS}) + 2.18$$

where *WEIGHT* is the weight of material detonated in a single shot in lb and the RMS is the observed root mean square (*RMS*) value in nm for a the first 20 seconds of the seismic signal observed at NV08.

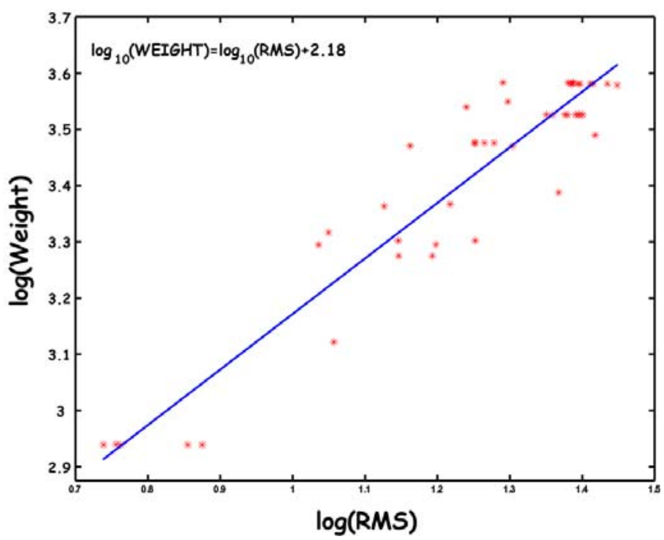

Figure 2. Calibrated weight/seismic relationship at NV08.

The smallest weights in the figure 2 are 868 lbs, while the largest are a little below 4,000 lbs, but there are no points between 868 and approximately 1,800 lb Explosions in this range are usually misfires and therefore no weight information is available. The error of the fit is approximately 10%, which also reflects changes in the chemical composition of the explosive cocktail. This relationship was updated several times when new logs were requested, but additional data affected only the second decimals in the constants, therefore it appears to be a reliable estimate of the actual yield of detonations.

Period/Yield Relationship

It should be noted that the frequency content of individual signals from low yield chemical explosions are affected by propagation. Tropospheric arrivals have higher dominant frequencies than stratospheric, and stratospheric arrivals are higher frequency than thermospheric arrivals. By far the most numerous types of arrivals are stratospheric and our analysis focused on them, though they are also the most difficult to analyze. The stratospheric signals are extremely complicated in the zone of silence (Figure 3). They are usually represented by several interfering signals which may or may not have the same frequency. Occasionally there could also be tropospheric and stratospheric interference which results in further interference. These characteristics lead to complex spectra which are difficult to interpret. The spectra of the signals observed at DNIAR are easier to interpret, but they also exhibit interference. The signals that were obviously contaminated or had low signal to noise ratio were not used in our preliminary yield/period relationship.

We have used a variety of methods in our attempt to determine the dominant period as accurately as possible. After filtering the data with a 2nd order Butterworth filter from 0.5 - 5 Hz and correcting for the instrument response we applied both the autoregressive technique and Fourier based methods to determine the dominant period. In the cases in which the signals had short durations the resolution in the frequency domain was poor but we obtained good results using a low order AR technique (order 8). However, in the case of complex signals even high order AR techniques (order 48) did not provide a good representation of the spectrum. In general AR techniques had comparable results with the Fourier based methods. Figure 3 shows some of the UTTR detonations that were available to us superimposed on the FNIAR observations.

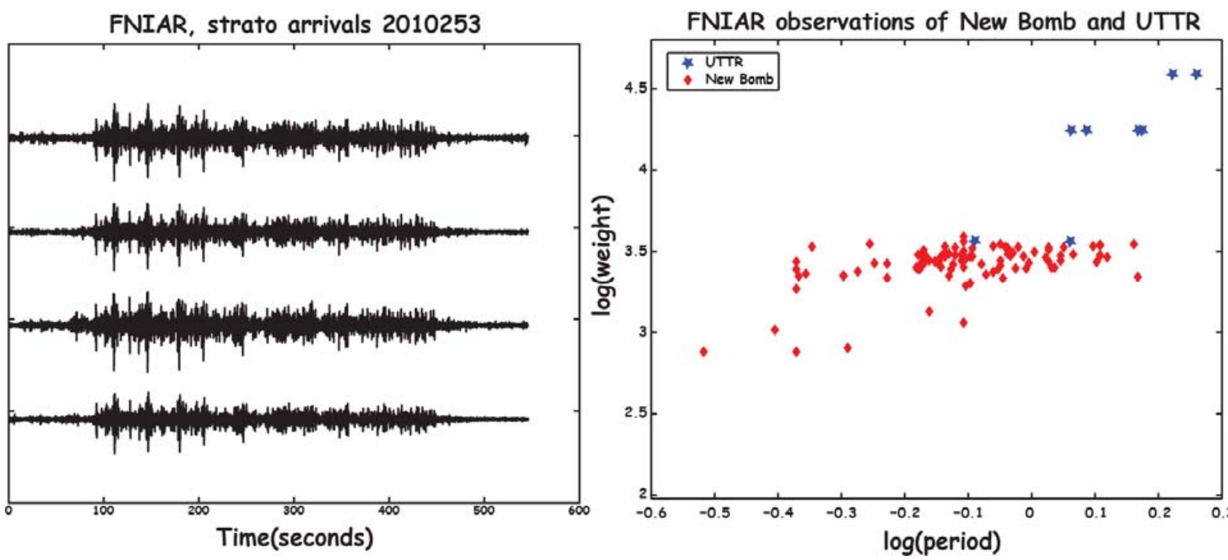

Figure 3. Observations of stratospheric signals at FNIAR (left) and period/weight plot for FNIAR observations of New Bomb and UTTR (right). Notice the variations in the morphology of stratospheric arrivals during a period of about 5 minutes.

The UTTR dataset that we analyzed consists of a few detonations from 2009 ranging in weight by an order of magnitude. The largest explosions are greater than 38,000 lbs, while the smallest we could detect are a little over 3,500 lbs, or approximately in the same range as the larger New Bomb detonations. Though we have few datapoints, the regression appears to be close to the cube root exponent that was inferred from the Armstrong (1988) relationship which has an exponent of 3.34, while our dataset gives 3.06. Of course, more data is needed in this range to accurately determine the slope, and this is one of the future areas of focus.

However, the New Bomb dataset does not follow the expected cube root relationship, and this may be due to propagation effects in the first bounce region ("Zone of Silence"). The exact propagation mechanisms in this range are poorly understood, and classic ray tracing does not predict these arrivals. There were a few cases when G2S models suggested the presence of a stratospheric inversion in the effective sound speed, but even in those cases the bounce points would have been at distances greater than 200 km, while FNIAR is located 154 km away. In order to explain these arrivals one needs to alter the effective sound speed to incorporate the effects of the gravity waves or finer atmospheric structures (Kulichkov, 2010). When compared to the few UTTR datapoints the New Bomb data appear to have a tail at periods shorter than 0.6 seconds (-0.2 value on the log period axis). Also it is not clear what the behavior is below 2-3,000 lb There were only a few detonations at New Bomb in this range, and we have detected only a fraction of those. They appear to be higher frequency than the 3,500 lb, but they are off the cube root slope that that is inferred from the UTTR shots. Only a few of the shots in that range were detected, but the preliminary conclusion is that below 2,500 lb the cube relationship does not hold. At very low yields the relationship should approach asymptotically to the origin point, and we may be seeing this effect. It should also be noted that those small yield detonations are on the detection threshold of our arrays. They were detected only in very low noise conditions. If the array was closer to the source, we may be able to detect lower yield explosions, but then the arrivals would probably not be stratospheric. Therefore it may not be possible to observe the behavior of the period/yield relationship at yields lower than about 900 lb

Tropospheric arrivals appear to be of limited use within the "Zone of Silence". They are usually monochromatic, and period determinations are not difficult, but the results are contradictory. High yield explosions could have dominant periods shorter than low yield explosions. It appears therefore that the frequency content of tropospheric arrivals reflects the propagation effects (thickness of inversion layer combined with topography effects). We did not detect a large number of thermospheric arrivals, therefore we do not have the necessary numbers to do a statistical analysis.

Amplitude Scaling

A field experiment carried out in June 2009 provided a dataset with enough observations to allow us to study how the amplitude scales with distance. We have deployed a total of 16 sensors at distances ranging from 2.5 to 176 km from New Bomb (Figure 1). During the four days in which atmospheric data was collected we had a great variability in the meteorological data. Figure 4 shows the effective sound speed profiles built from the actual meteorological measurements and the corresponding rays.

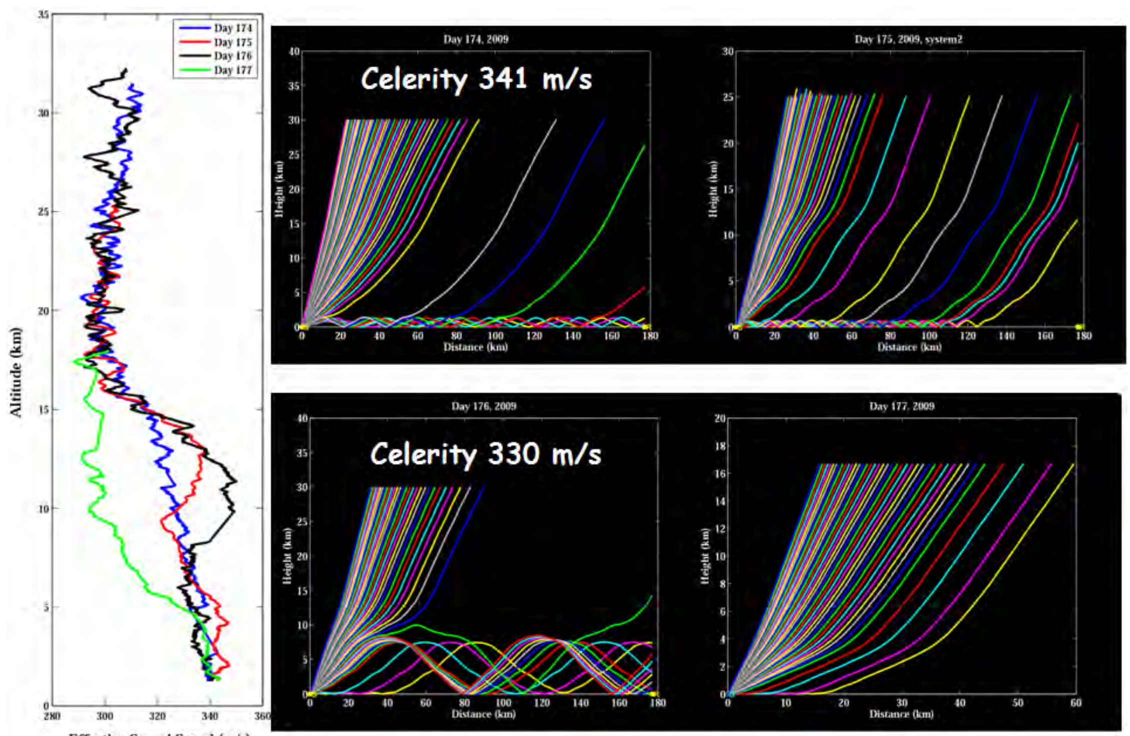

Figure 4. Effective sound speed and corresponding rays for a line of sensors deployed north of the New Bomb site to 176 km.

During Julian Day, 1976, we observed an inversion in the effective sound speed between 8 and 12 km due to the jet stream, while during the rest of the days raytracing suggests the observed arrivals propagated in near surface ducts. No stratospheric arrivals were observed except for the last day and those occurred at distances over 154 km. Due to the proximity of the sensors to highways this dataset is relatively noisy and it was difficult to identify the actual arrivals at all stations. Figure 5 shows the observed amplitudes of the tropospheric arrivals and the least square fit through the dataset. All the detonations were 3809 lbs of mixed ordnance. What is interesting is that the amplitudes of all arrivals observed from the low altitude duct decay in the same way, while the jet stream propagation is affected by focusing and defocusing effects.

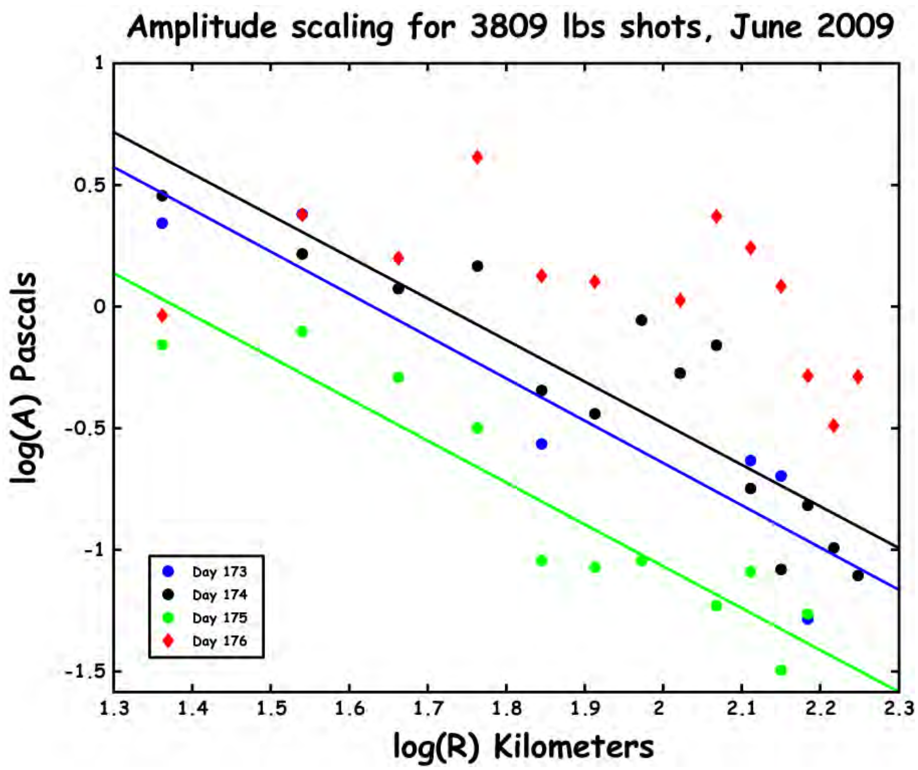

Figure 5. Amplitude versus range for 3809 lbs of mixed ordnance.

There are several scaling relationships that were published in literature that we applied to our dataset. Some of them were summarized in a paper by Stevens et al. (2002):

$$log(P) = - 1.54 + log(W) - 0.5\ (R sin\Delta),$$ (Pierce and Posey, 1971)

$$log(P) = 0.92 + 0.5\ log(W) - 1.47\ log(\Delta),$$ (Clauter and Blandford, 1998)

$$log(P) = 3.37 + 0.68\ log(W) - log(R),$$ (Whitaker, 1995)

$$log(P) = 3.00 + 0.33\ log(W) - log(R),$$ (used by Russian scientists)

Where P is the zero to peak pressure in Pascals, W is the yield in kt, R is the distance in km and Δ is the distance in degrees. All formulas were developed from datasets of nuclear explosions, and therefore we applied a correction for the chemical energy release. Considering that a chemical explosion releases half of the energy released by a similar yield nuclear explosion, we have applied the following correction:

$$log(P_C)=log(P_n)-log(2)$$

Where P_C is the pressure observed from a chemical explosion and Pn is the pressure observed from a nuclear explosion. A second correction that we applied is the wind correction. The role of the formula is to correct observed pressure to zero wind conditions (methodology used in the LANL formula). The correction is:

$$log(P_{cor})=log(P_{raw}) - 0.018V_d$$

where P_{cor} is the corrected zero to peak pressure amplitude, P_{raw} and V_d is the maximum wind in the propagation direction.

The results for these relationships are shown in Figure 6. The best result is obtained by the Clauter and Blandford (1998), formula, while Pierce and Posey (1971) is not a good fit. Stevens (2002) found that the Pierce and Posey formula, a theoretical derivation for the Lamb edge excitation fits relatively well with Lamb waves observed for very large nuclear explosions (yields larger than 1 Mt), but performed poorly for the rest of their dataset. The slope of the LANL formula (Whitaker, 1995) is closer to the best fit line as opposed to the formula used by Russian scientists, who consider the pressure to be proportional to the cube root of distance. The LANL formula was derived empirically on a dataset of stratospheric arrivals and makes use of wind corrected amplitudes, while our dataset is composed of only tropospheric arrivals, but we chose to show it just for illustration purposes.

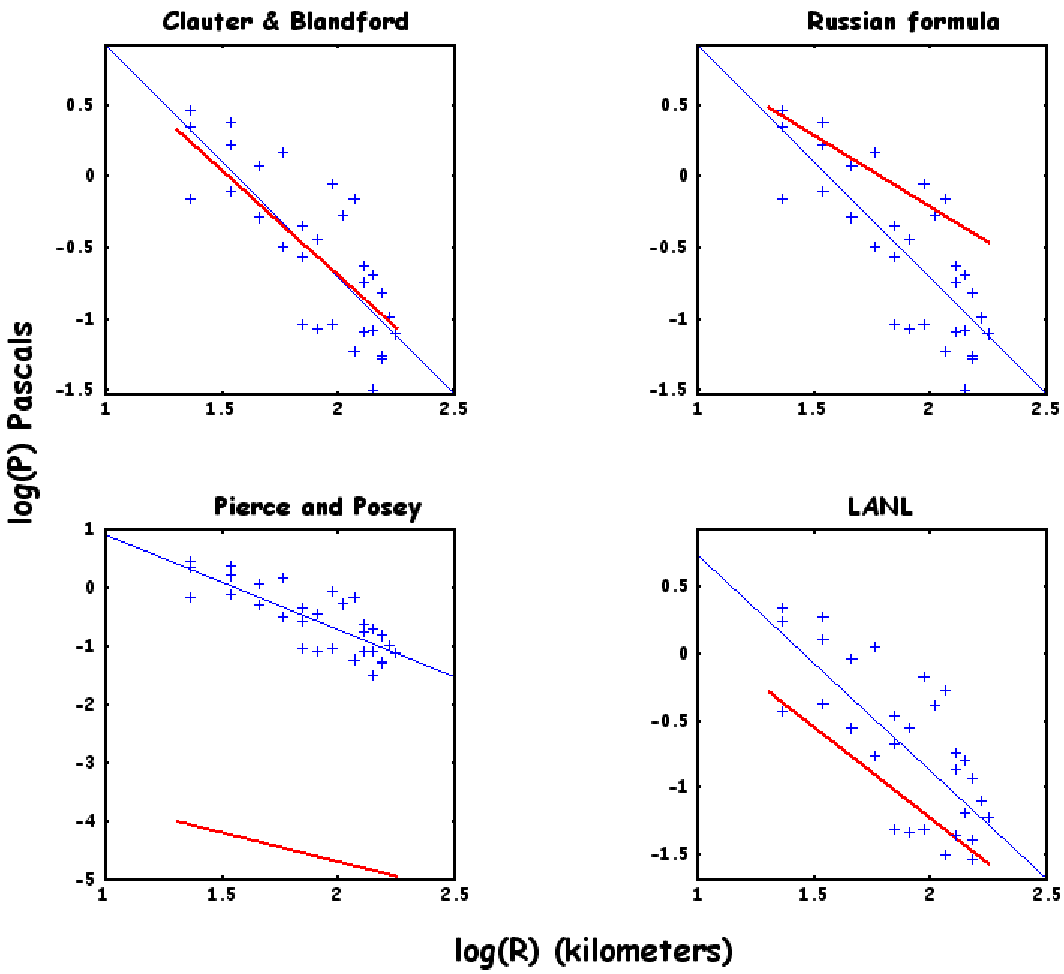

Figure 6. Wind corrected amplitude versus range observations and best fit. Also shown are the estimates using different formulas.

Figure 7 shows our best fit starting from the ANSI relationship ($A_0=C(R/W^m)^p$), where A_0 is the amplitude, W is weight R is the distance and C, p and m are proportionality constants). Our approach was a little different than the previous scaling studies in that we determined the p values empirically taking advantage of the fact that all detonations are of similar yield. Therefore a $log(A_0)$ versus $log(R)$ plot would find the p value, assuming that W is constant. The value for p that we determine empirically is -1.63, and is a little different than what is usually inferred for p (-1.2 to -1.5). Differences in the constants are usually explained in variations of the wavefront geometry (spherical versus cylindrical wavefronts) corresponding to near and far field observations.

It should be noted that the variance of pressure amplitudes are nearly one order of magnitude for days 173 to 175. Winds in excess of 30 m/s are needed to lower this variance, but such values are observed only for Jetstream propagation, not for near surface ducts. Similarly we have observed very large variations in the amplitudes of the stratospheric arrivals (more than order of magnitude), for essentially same atmospheric (wind) conditions. It appears therefore that it is more difficult to estimate the infrasonic yield from amplitudes, at least within this distance range.

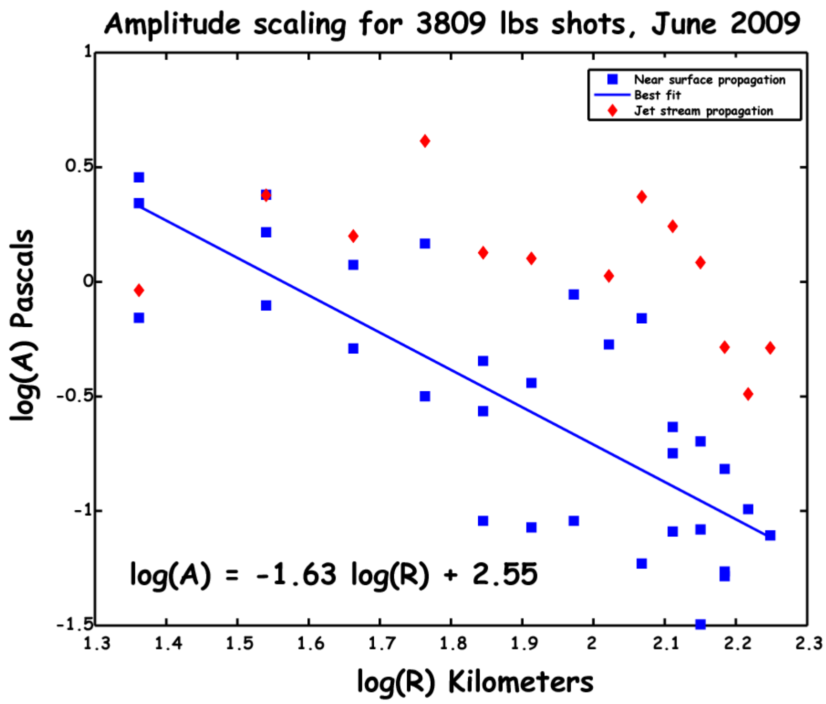

Figure 7. Regression of the dataset for near surface propagation.

The Blast Operational Overpressure Model (BOOM) of Douglas (1987), does not fit this dataset well. One possible explanation is that our meteorological data does not reflect the near source conditions that are needed for the BOOM. The data was collected at the Hawthorne airport, approximately 20 miles away and 600 m lower in elevation than the New Bomb location.

CONCLUSIONS AND RECOMMENDATIONS

The dominant period/yield relationship in general exhibits a cube root behavior above weights of about 2,500 lb However, below that weight the relationship appears not to follow the cube root scaling law, and it may roll off towards the origin point. Also, the New Bomb dataset appears to have a tail at higher frequencies that may be related to the mechanisms of propagation in the “Zone of Silence.” Thermospheric and tropospheric arrivals are of limited use in this distance range.

Yield determinations based on infrasonic amplitudes are more difficult to apply. A one week field experiment revealed that the amplitude of near surface tropospheric arrivals decay in a similar matter, though they exhibit nearly one order of magnitude in variance. This scatter was not significantly reduced when a wind correction was applied.

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