SAND XXXX-XXXX
SAND2017-3812C

Acoustic Yield Estimation using full waveforms

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Abstract

A method for estimating the yield of explosions from shock-wave and acoustic-wave measurements is presented. The method exploits full waveforms by comparing pressure measurements against an empirical stack of prior observations using scaling laws. The approach can be applied to measurements across a wide-range of source-to-receiver distances. The method is applied to data from two explosion experiments in different regions, leading to mean relative errors in yield estimates of 0.13 using prior data from the same region, and 0.2 when applied to a new region.

Method

The method described in this poster exploits a rich dataset of shock wave and acoustic observations from explosions of known yield. The method is based on the fact that observations from multiple surface explosions, with known but different yields, can be plotted on a single scaled-time/scaled-range plot (e.g., Figure 1). Prior to estimating the yield of a new explosion, observations from previous ground-truth experiments are stacked by averaging sampled pressure observations in scaled time and scaled range bins. In this study, we generated stacks by averaging pressure observations from 0 to 700 m/kg^1/3 and -0.005 s/kg^1/3 to 0.03 s/kg^1/3 in bins of 20 m/kg^1/3 and 0.0001 s/kg^1/3 (Figure 1). The minimum and maximum scaled times and ranges were chosen to capture the full set of pressure-time measurements from the observational dataset used in this study. The bin dimensions used are a compromise between resolution and noise reduction through averaging.

Following Kinney and Graham (1985), scaled time and distance are defined relative to the observed time and distance by:

$$t_{\mathrm{sc}} = \left(\frac{f_c}{W^{1/3}}\right) t \qquad r_{\mathrm{sc}} = \left(\frac{f_d}{W^{1/3}}\right) r$$

where W is yield in kilograms (TNT equivalent), and:

$$f_t = \left(\frac{p_{\mathrm{obs}}}{p_{\mathrm{ref}}}\right)^{1/3} \left(\frac{T_{\mathrm{obs}}}{T_{\mathrm{ref}}}\right)^{1/6} \qquad f_d = \left(\frac{p_{\mathrm{obs}}}{p_{\mathrm{ref}}}\right)^{1/3} \left(\frac{T_{\mathrm{obs}}}{T_{\mathrm{ref}}}\right)^{-1/3}$$

scale for the ambient pressure and temperature relative to reference values.

To estimate the yield of a new explosion, we perform a grid search whereby observed data at a given range are converted to scaled range by assuming a trial yield. This waveform is compared against the corresponding stack record, with data transformed into units of scaled time relative to an arrival time pick. The estimated yield is thus the trial yield that results in the minimum normalized root-mean-square residual over all observations. The residual from M sensors, where each sensor is at a different geographic location, can be defined as:

$$\gamma(W) = \frac{1}{M} \sum_{i=1}^{M} \left[\frac{1}{N} \sum_{j=1}^{N} \frac{[p_j - \bar{p}(W)_j]^2}{p_i^{max}/p_i^{min}} \right]^{1/2}$$

where $\mathbf{p} = [p_1, p_2, ..., p_n]$ are scaled-time binned pressure observations at a given station, and $\bar{\mathbf{p}} = [\bar{p}_1, \bar{p}_2, ..., \bar{p}_n]$ is the empirical stack for the scaled range closest to the true scaled range for the trial yield, and $p_i^{\max}$ and $p_i^{\min}$ are maximum and minimum values of the pressure at the i'th sensor.

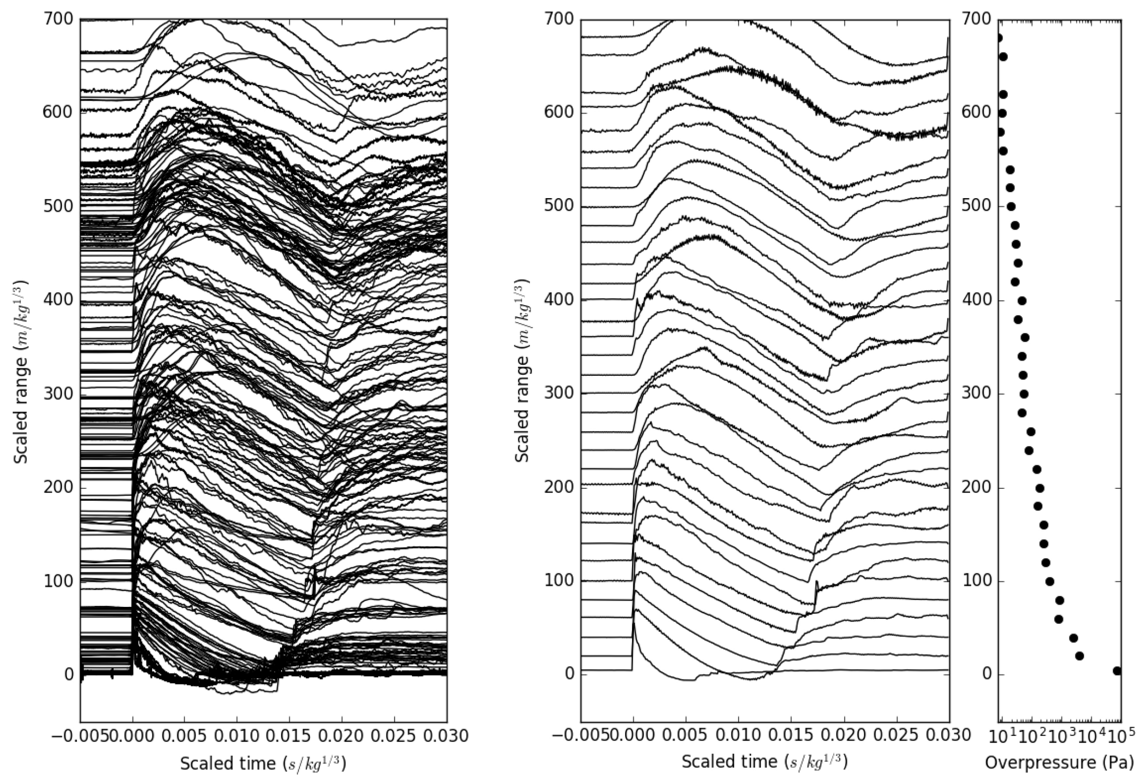
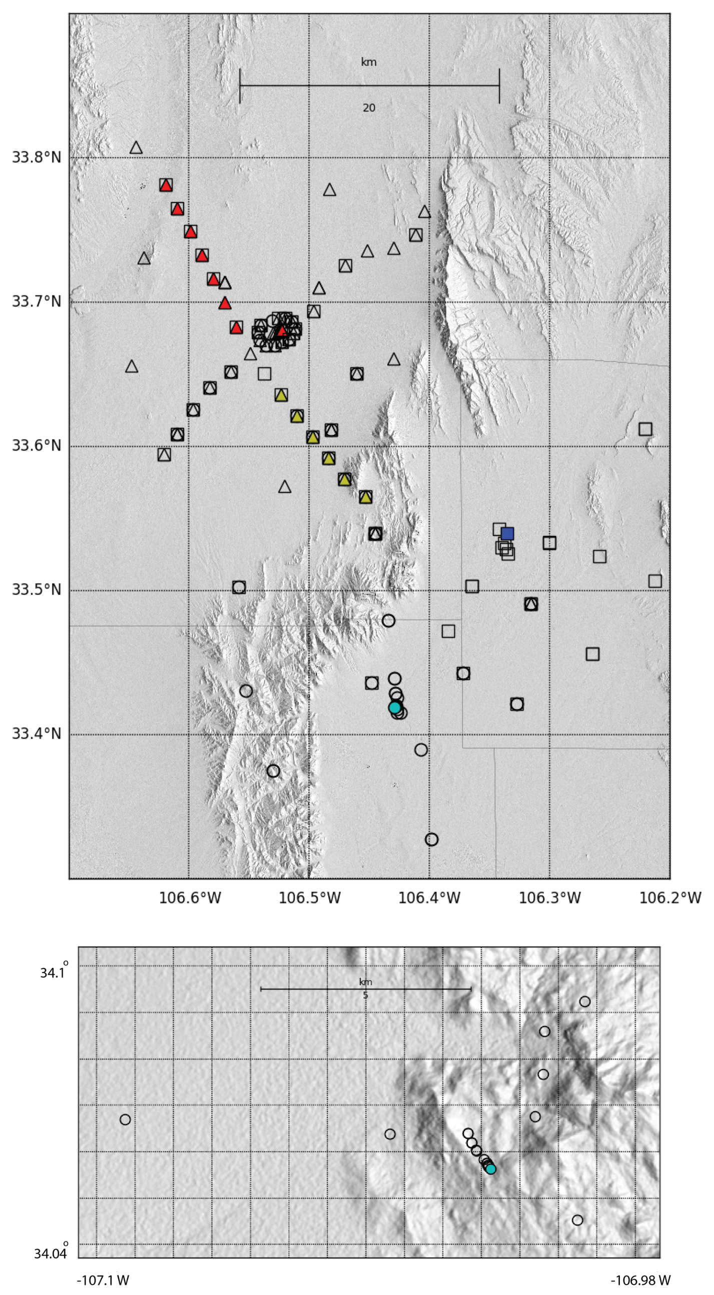


FIGURE 1. Picture of the stack showing raw waveforms for HRR-1, HRR-4, HRR-5, and HRR-6 (left panel), averaged waveforms (center panel) and peak overpressure amplitudes of the averaged waveforms (right panel). Scaled times are plotted relative to analyst-derived arrival time picks. The stack in the middle panel was used to estimate the yield for HRR-3.

Dataset



The Humming Roadrunner (HRR) experiment was a series of chemical explosions conducted at the White Sands Missile Range (WSMR) in New Mexico (these events were also studied by Kim and Rodgers, 2016, and Bonner et al., 2013). Five shots (Figure 2) were conducted at or above the ground-surface and provide the primary testing dataset for this study. For each shot, a dense network of overpressure and acoustic sensors were deployed, and digitized at 1000 Hz (Figure 2). The Humming Tarantula (HTA) experiment was a series of much smaller explosions detonated at the Energetic Materials Research and Testing Center near Socorro, New Mexico, in January and February of 2015 (Figure 2). Here, we only use the above-ground shots, HTA1 - HTA3, which were conducted at height-of-bursts ranging from 0.6 to 4.8 m. For each shot, a network of NSTech overpressure instruments and Hyperion infrasound sensors were deployed.

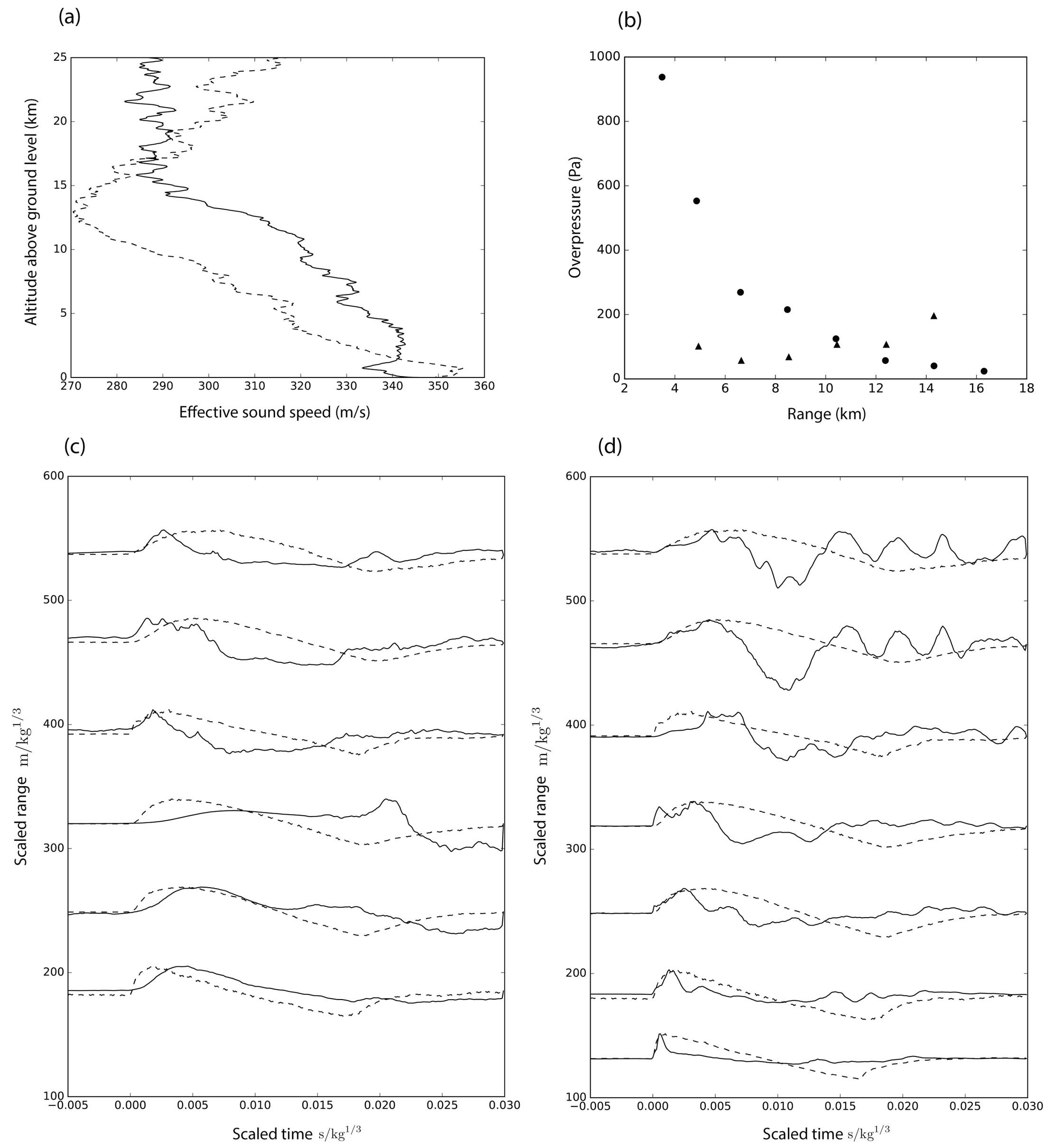
FIGURE 2. Maps of the source and sensor locations for the HRR (top) and HTA (bottom) experiments. In the top panel, colored symbols represent sources (cyan circle = HRR-1, red triangle = HRR-3 and HRR-4, blue square = HRR-5 and HRR-6) and open symbols represent sensor locations (circles = HRR-1, triangles = HRR-3 and HRR-4, and squares = HRR-5 and HRR-6). Stations to the NW and SE of HRR-3 used in the analysis presented in Figure 3 are filled red and yellow respectively. In the bottom panel, the circle is the source location for each shot, and open circles show sensor locations. In each panel, topography is shaded with a light source.

Results

To assess the method described above on the HRR data, we performed a leave-one-out test whereby we estimated the yield for each of the five HRR explosions in Table 1 using the other four HRR explosions to generate the empirical stack. In each case, we generated a stack by averaging all observations from the other four explosions. The stack was then used to estimate the normalized RMS residual for a set of 50 trial yields, logarithmically spaced from 100 – 100,000 kg, with the estimated yield taken as the yield resulting in the minimum residual. The resultant yield estimates, shown in Table 1, result in similar relative errors, |(W_est-W_true)/W_true |, to the results published by Kim and Rodgers (2016) which was based on finite difference modeling – our yield estimates were closer for three shots, while the results of Kim and Rodgers were closer for two shots.

Shot Number	TNT Equivalent yield (kg)	Estimated yield (kg)	Estimated yield (Kim and Rodgers)	Relative Error (this study)	Relative Error (Kim and Rodgers)
HRR-1	18144	21210	17300	0.17	0.05
HRR-3	9072	6870	9300	0.24	0.03
HRR-4	9072	9700	12100	0.07	0.25
HRR-5	45359	49400	61000	0.09	0.34
HRR-6	45359	49400	58800	0.09	0.30
HTA-1	227	355	N/A	0.36	N/A
HTA-2	227	233	N/A	0.03	N/A
HTA-3	227	175	N/A	0.23	N/A

TABLE 1. Comparison between estimated and true yields for each HRR and HTA shot. HTA estimated yields are evaluated using a stack formed from HRR data.



To further explore the method, we apply the technique separately to observations taken along two profiles to the NW and SE of HRR-3 (the stations used are colored red and yellow in Figure 2). The observations of this shot exhibited very strong azimuthal effects that are caused by a storm front that passed through the study region at the time of the event. Radiosonde measurements, taken 30 minutes before the shot, show quite different propagation environments to the NW and SE (Figure 3). These different propagation environments are manifest in the overpressure observations, which decrease with range to the NW but remain steady to the SE due to a strong directional wind-driven waveguide (Figure 3). Despite such strong azimuthal differences, our method results in yield estimates of 8697 kg when using only the stations to the NW (a relative error of only 0.04) and 6135 kg when using only the stations to the SE (a relative error of 0.32).

FIGURE 3. Application of the template matching method to HRR-3 observations to the NW (red triangles in Figure 2) and the SE (yellow triangles in Figure 2) of the shot. (a) Effective sound speed profiles to the NW (dashed line) and the SE (solid line) from a radiosonde that was launched adjacent to the shot site 30 minutes prior to launch. (b) Overpressure measurements taken along the NW (circles) and SE (triangles) profiles. (c) A comparison between the observed data (solid lines) and stack data (dashed lines) along the NW profile, with observations scaled by the true yield. (d) as (c) for the SE profile.

References

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