A New Experimental Field Study of the Effects of Explosive Detonation Products on Seismic Radiation

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ABSTRACT

Weston Geophysical Corp. conducted a series of chemical explosions using various explosives with different properties to investigate their effect on seismic signatures. Previous experimental data from the New England Damage Experiment (e.g., Martin *et al.*, 2012) suggest that low-frequency *P*-wave amplitudes are affected by the explosive velocity of detonation and by the thermodynamic characteristics of gaseous explosive products (Stroujkova, 2015). The new experiment conducted in New Hampshire in 2016 was designed to isolate the effects of the amount of the explosive gases using aluminized and nonaluminized explosive pairs. The explosions were recorded using a network of seismometers and accelerometers fielded from near-source to local distances. Seismic data from this experiment provide ground-truth data that may be useful for future comparative studies of yield, based on seismic-waveform analysis.

Electronic Supplement: Tables of station information.

INTRODUCTION

Weston Geophysical Corp. (WGC) conducted an active source explosion experiment (GAS2016 experiment) using aluminized and nonaluminized explosive pairs to study the effect of gaseous detonation products released during explosions on seismic radiation. The experiment was conducted in August 2016 near Carroll, New Hampshire, and included six explosions with yields between 63.1 and 96.2 kg of trinitrotoluene (TNT) equivalent and three calibration shots of 0.454 kg of composition B (COMP B). The TNT equivalent yield for different explosives is determined by expressing the energy released during explosive detonation in terms of energy units corresponding to the energy released by detonation of 1 kg of TNT or $Q_{\mathrm{TNT}} = 4184\,\mathrm{kJ/kg}$.

The objective of the experiment is to investigate the effect of the volume of the gases released into the explosive cavity on the seismic radiation. Our analyses of the experimental data from the New England Damage Experiment (NEDE; e.g., Martin *et al.*, 2012; Stroujkova *et al.*, 2012) suggest that the low-frequency spectral asymptotes are determined not only by the explosion yield but also by the amount of released gas (Stroujkova, 2015). The explosives utilized during NEDE had different detonation velocities, which affected the pressure in the explosive cavity. This study utilized the explosive pairs with similar (within 5%) detonation velocities but different volumes of detonation products. Differences in the volumes of the detonation products were achieved by adding aluminum powder to the explosive mix to reduce the amount of gas and increase the heat of the explosion. Aluminized explosives generate extremely large amounts of heat from the highly exothermic heat of formation for aluminum oxide ($\Delta H = -1676\ \mathrm{kJ/mol}$; e.g., Chase, 1998), producing significantly higher temperatures than nonaluminized explosives. Free oxygen reacts with aluminum powder to produce aluminum oxide by the reaction: $2\mathrm{Al} + 1.5\mathrm{O}_2 \rightarrow \mathrm{Al}_2\mathrm{O}_3$. As a result, there is a decrease in volume of gaseous detonation products for aluminized explosives. Because more energy is transferred to thermal energy, less radiates as seismic waves, resulting in decreased coupling. In addition, some of the explosions were conducted in water-filled boreholes to quantify the effect of water surrounding the charge on seismic radiation.

The explosions were recorded by a network of seismometers and accelerometers. The dataset contains data from 34 short-period seismometers and 11 accelerometers fielded from near-source to local distances.

The dataset can improve our understanding of seismic waves generated by explosions. The data can be used for research related to seismic explosion monitoring, such as seismic-event detection, discrimination, and characterization. It may also provide ground-truth events for regional seismic studies in New England.

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Table 1
Characteristics of the Explosions

Shot	Date (yyyy/mm/dd)	Origin Time (GMT) (hh:mm:ss.sss)	Latitude (°)	Longitude (°)	Depth (m)*	Explosive Type	Yield (kg TNT)	Condition†
SH1	2016/08/11	23:30:31.045	44.29417	−71.55435	12.95	TNT	63.2	D
SH2	2016/08/11	19:08:46.404	44.29436	−71.55422	13.00	Tritonal	96.2	D
SH3	2016/08/12	14:41:35.217	44.29429	−71.55456	12.65	TNT	63.2	WF
SH5	2016/08/11	22:13:25.735	44.29399	−71.55448	12.70	ANFO	63.1	D
SH6	2016/08/11	21:17:56.761	44.29410	−71.55409	12.65	ANFO/Al	94.1	D
SH7	2016/08/12	18:37:38.152	44.29387	−71.55423	12.50	ANFO	60.9	WF
CA1	2016/08/12	20:00:35.512	44.29406	−71.55430	12.80	COMP B	0.5	WF
CA2	2016/08/12	20:01:35.979	44.29402	−71.55459	12.50	COMP B	0.5	WF
CA3	2016/08/12	20:02:36.402	44.29430	−71.55438	10.97	COMP B	0.5	WF

ANFO, ammonium nitrate and fuel oil; COMP B, composition B; TNT, trinitrotoluene.
*The depth indicates the borehole depth below the surface prior to loading of the charges.
†Borehole condition indicates whether the charge was placed into a dry (D) or water-filled (WF) borehole.

EXPERIMENT DESIGN AND INSTRUMENT DEPLOYMENT

The experiment was conducted in a granite quarry near the town of Carroll, New Hampshire. Six single-shot explosions and three calibration shots were conducted during the experiment (Table 1). The following explosives were used to conduct the shots: TNT, tritonal (TNT/Al 80/20), ammonium nitrate and fuel oil (ANFO), and aluminized ANFO (ANFO/Al 80/20). In addition, COMP B boosters were used to initiate the charges and to perform the calibration shots. All explosions were conducted in boreholes of similar depths between 12.5 and 13 m, which were stemmed with crushed stone after loading the charges.

To compare the performance of aluminized and nonaluminized explosives, equal weight TNT and tritonal charges were detonated in dewatered boreholes (SH1 and SH2, respectively). Shots SH1 and SH3 were conducted using identical TNT charges; however, SH1 was detonated in a dry borehole, whereas SH3 was placed into a water-filled borehole. Both TNT charges had assembled lengths of 1.25 m, whereas the tritonal charge had a length of 1.19 m. Thus, the emplacement geometry for the TNT/tritonal explosion series was very similar.

In addition, a pair of aluminized and nonaluminized ANFO shots of equal weights were detonated in dry boreholes (SH5 and SH6, respectively). The charges were loaded into the hole liners placed directly into the boreholes. The lengths of both SH5 and SH6 charges were ∼2.1 m. For the last shot (SH7), the borehole wall was narrowed to less than 20 cm, due to the ground shock from previous shots; therefore, we were unable to use the charge with a 20 cm diameter. As a result, the SH7 charge was composed of two segments with diameters of 15 and 16.25 cm. The total length of the charge was ∼4 m, compared to the length of the ANFO charge (SH5) of ∼2.1 m.

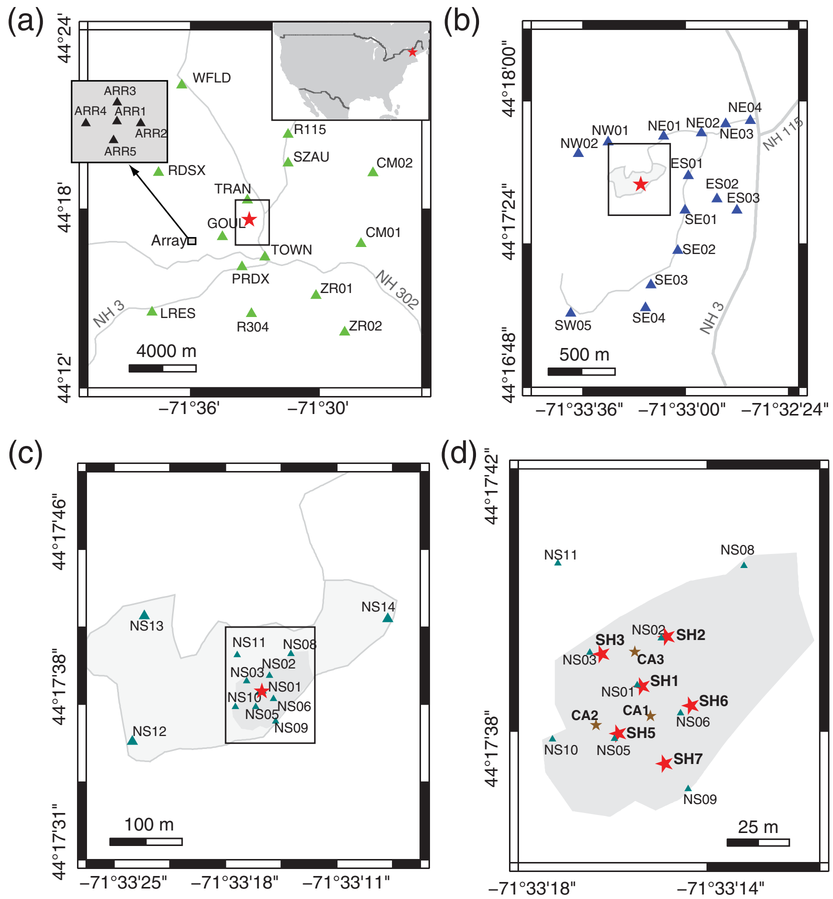
The deployment of the seismic network started on 9 August 2016 and was completed on 11 August 2016. The shots were conducted on 11–12 August, followed by the network removal, which was finished on 13 August.

A 45-station seismic network was fielded from near-source to local distances (between 1.5 m and 9.4 km), including short-period seismometers and accelerometers (Fig. 1). The station information is provided in Ⓔ Table S1, available in the electronic supplement to this article. All of the instruments recorded three components (3C) of motion using RefTek 130 (RT130) data loggers.

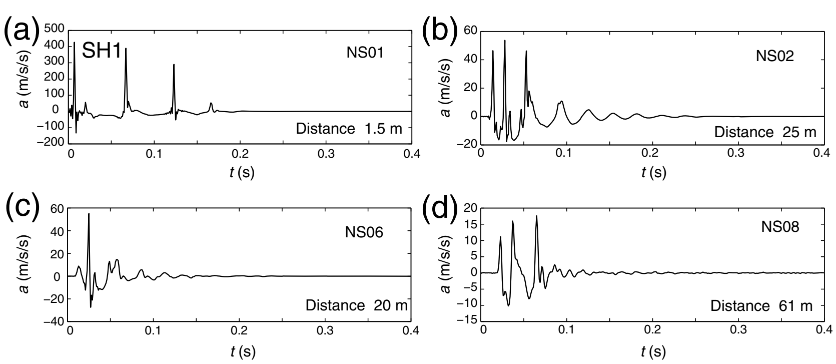
Five Endevco 25*g* accelerometers and six TerraTech 4*g* accelerometers were installed in close proximity to the explosions to record the near-source ground motions (Fig. 1c,d). The near-field accelerometers were placed at lateral distances between 1.5 and 200 m from the sources and grouted in-place to provide better coupling. One of the close-in stations (NS14) located at a distance of ∼200 m from the sources was equipped with a short-period Trillium Compact sensor. The recording equipment was placed in plastic tubs for protection. These stations recorded at a sampling rate of 1000 samples per second.

Fourteen near-source short-period seismometers were fielded at distances between 0.3–1.2 km from the explosions (Fig. 1b; Ⓔ Table S1). Six of the near-source stations utilized Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) BIHO boxes (quick deploy boxes) and were equipped with 2-Hz Sercel L22 2 Hz 3C sensors. The remaining eight near-source stations used 1-Hz L-4C 3D sensors. These stations were recording continuously with a sampling rate of 500 samples per second.

In addition, 19 stations were installed off the quarry property at local distances between 1.2 and 9.4 km (Fig. 1a; Ⓔ Table S1). All of these stations were equipped with PASSCAL BIHO boxes with 2-Hz Sercel L22 2 Hz 3C sensors. The



▲ **Figure 1.** (a) Seismic stations deployed at local distances from the explosions near Carroll, New Hampshire. The green triangles show the local stations, and the star shows the shot points. The inset in the upper right shows the map of the continental United States with the experiment location marked as a red star. The inset in the upper left shows the configuration of a short-period array, deployed in the area marked as a rectangle. The rectangular area surrounding the experiment site is enlarged in (b). (b) The near-source network of the short-period seismometers. The blue triangles show the 3C stations (L22). The area within the rectangle is enlarged in (c). (c) Enlarged view showing the near-field accelerometers (teal triangles). (d) Enlarged view of the test site, showing the shot locations (red stars) and the near-source accelerometers. The locations of the calibration shots are shown as brown stars.



▲ **Figure 2.** Accelerograms (vertical components) for SH1 recorded by the near-source accelerometers: (a) NS01, (b) NS02, (c) NS06, and (d) NS08.

stations were recording continuously with a sampling rate of 500 samples per second using RT130 digitizers, with the exception of several stations (GOUL, CM01, CM02, R115, RDSX, SZAU, and ARR3) recording at 250 samples per second. The White Mountains National Forest with its rugged terrain is located to the east and south of the explosion site. Stations ZR01, ZR02, LRES, R304, CM01, and CM02 (Fig. 1a) are located in the National Forest. The area to the west and north of the test site is somewhat less rugged. The stations in that area were located on residential properties, whereas two of the sites TOWN and TRAN were located on municipal property belonging to the town of Carroll, New Hampshire. All of the local data were recovered.

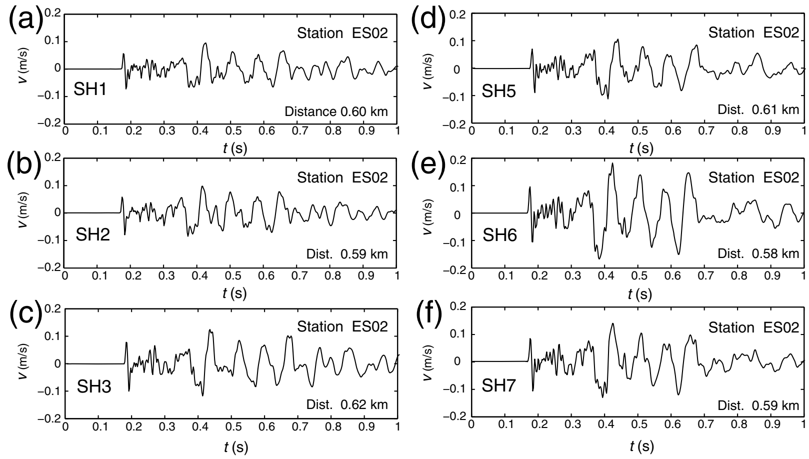
A short-period five-element seismic array was deployed as a part of the local network ~3.75 km from the sources to study local phase propagation. The array configuration is shown on the inset in Figure 1a. The largest distance between the array elements is ~168 m (ARR2–ARR5), and the shortest distance between the elements is ~41 m (ARR1–ARR3). Four of the array stations were recording with a sampling rate of 1000 samples per second, whereas one of the stations (ARR3) was erroneously set to 250 samples per second (possibly due to malfunctioning equipment).

The explosion origin times were determined using the Weston Inexpensive Timing System, (WITS) designed as a loop wire forming a closed circuit with a low voltage recorded with a high-sample-rate digitizer (RT130). Timing accuracy for the WITS system is 2 ms.

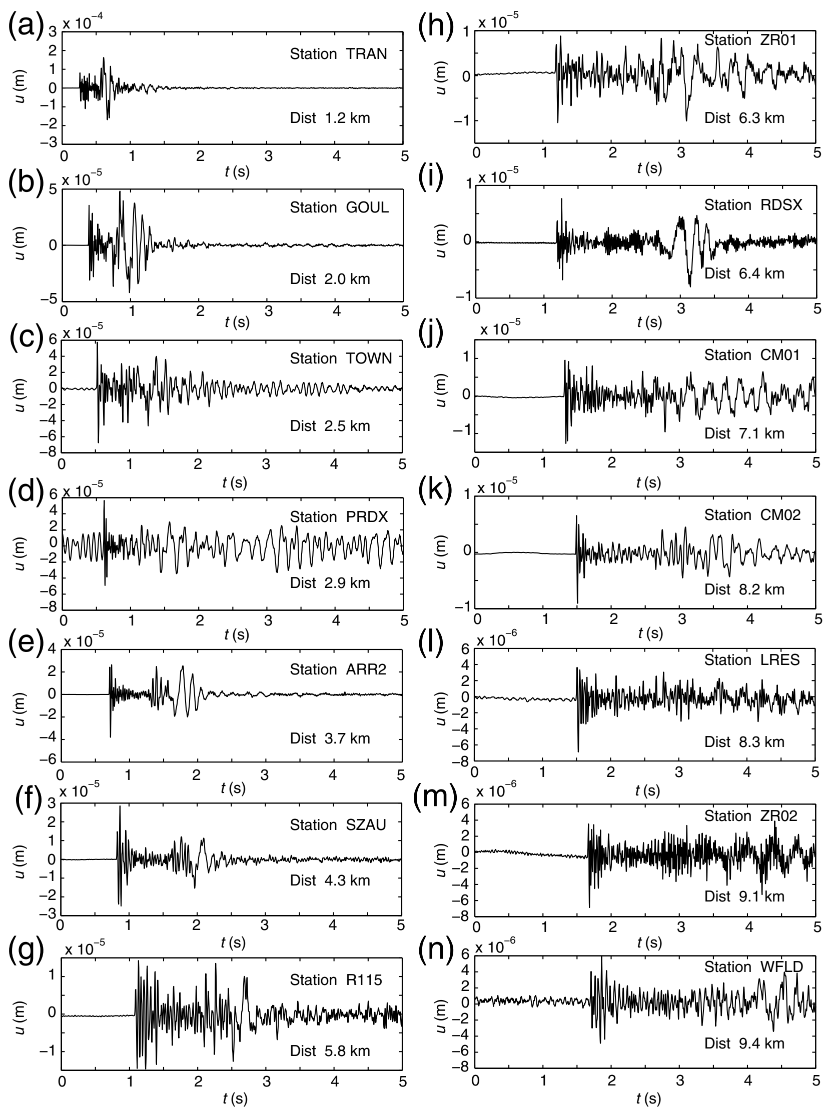
The velocity of detonation (VOD) was measured using a MREL HandiTrap II VODR. A resistance wire is taped to the booster and lowered down the hole. As the detonation wave propagates up the borehole, the resistance wire is melted, and the recorder measures the decreasing resistance at 1 million samples per second. The resistance is then converted to distance and a velocity calculated.

OVERALL DATA QUALITY AND AVAILABILITY

We recovered 94% of the data. A limited number of strong-motion accelerometers prevented us from recording every shot at every near-source instrument location. The near-source accelerometer locations were chosen for each shot to provide the optimal sensor geometry. Ⓔ Table S2 provides information on which



▲ **Figure 3.** Vertical components of the velocity seismograms recorded by short-period station ES02 for (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6, and (f) SH7.



▲ **Figure 4.** Vertical components of the displacement seismograms for SH1 recorded by the local stations: (a) TRAN, (b) GOUL, (c) TOWN, (d) PRDX, (e) ARR2, (f) SZAU, (g) R115, (h) ZR01, (i) RDSX, (j) CM01, (k) CM02, (l) LRES, (m) ZR02, and (n) WFLD.

near-source accelerometer was operational for each shot. One of the Endevco cables was damaged from previous explosions; therefore only four of these sensors were recording at each time. Station NS10 had a malfunctioning vertical component, whereas station NS12 had malfunctioning horizontal components. All of the data recorded at distances over 200 m was recovered.

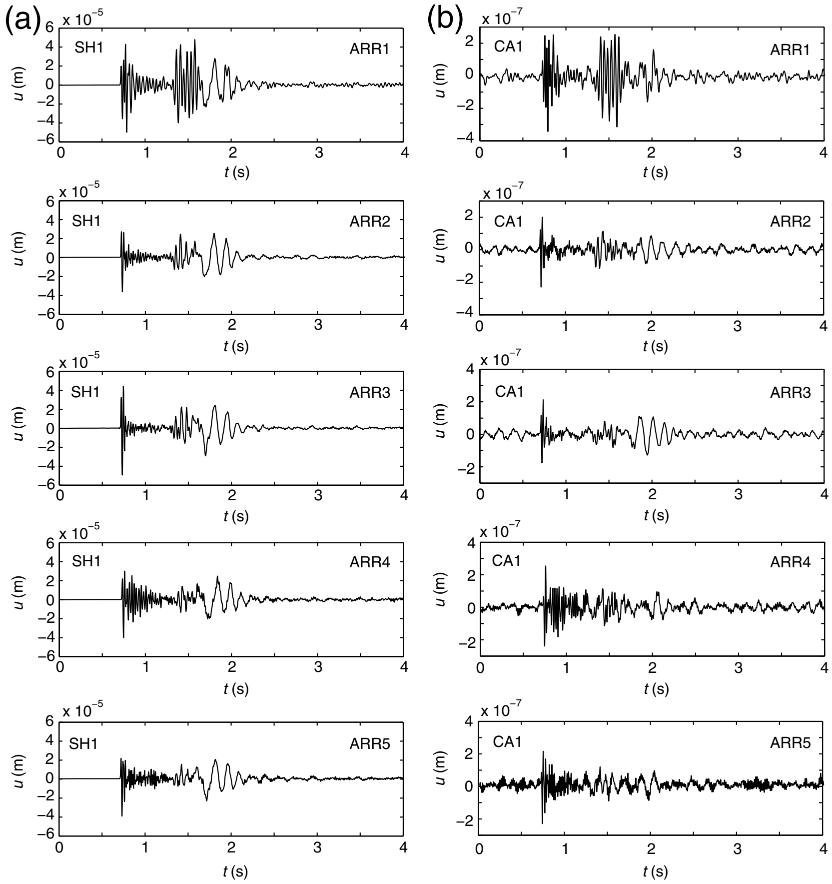
INITIAL OBSERVATIONS

The objective of the experiment was to document the differences of the waveforms and spectra due to differences in the explosive gaseous products. Four of the shots conducted using nonaluminized explosives had similar TNT equivalent yields (Table 1). The remaining two shots were conducted using aluminized explosives with the same weights of the explosives as their nonaluminized counterparts (TNT and tritonal, ANFO and aluminized ANFO), but their TNT equivalent yields were higher, due to an addition of aluminum.

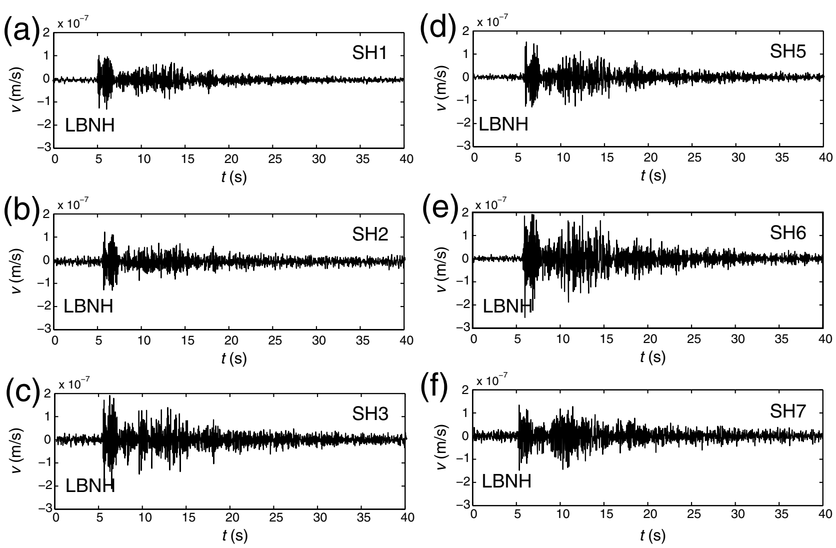
Examples of the near-source accelerometer records from the TNT shot SH1 are shown in Figure 2. The sensor located at the surface 1.5 m from the shot borehole (NS01) recorded an impulsive shock-wave arrival, followed by a period of downward acceleration close to $-1g$ (dwell) and then a series of spikes resulting from the slapdowns.

Figure 3 shows the recorded seismic traces from station ES02 fielded ~620 m from the source array. SH1 (TNT) and SH2 (tritonal) amplitudes are nearly identical for ES02 (Fig. 3a,b), as well as for other stations of the network, even though SH2 has a larger yield by a factor of 1.53. We hypothesize that similar amplitudes from SH2, despite larger yield, are caused by reduced coupling due to the smaller amount of gaseous products released during tritonal detonation. The amplitudes produced by aluminized ANFO (SH6) are, however, higher than the amplitudes from the ANFO shot (SH5) with a similar yield ratio near 1.5 (Table 1). SH6 shows the highest amplitudes at ES02 for both *P* and *Rg*. The amplitude ratios between the shots recorded at other near-source (0.4–1.2 km) and local (1.2–9.4 km) stations are consistent with the ratios observed at station ES02. The effect of the explosive properties on seismic amplitudes and spectra is a subject of our ongoing research.

Seismic waveforms recorded at the near-source distances have high signal-to-noise ratios



▲ **Figure 5.** (a) Vertical displacements for SH1 recorded by the short-period array (stations ARR1–ARR5). ARR1 is the central element of the array, located ~3.75 km from the explosions. (b) Vertical displacements for the calibration shot CA1 recorded by the short-period array.



▲ **Figure 6.** Vertical components of the velocity seismograms recorded by the permanent station LBNH located ~30.2 km from the shots in Lisbon, New Hampshire for (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6, and (f) SH7.

(SNR) for both larger explosions and for the small calibration shots. Figure 4 shows the local waveforms from SH1 at ranges from 1.2 km (station TRAN) to 9.4 km (station WFLD). As expected, the SNR degrades with the increase in range. Cultural noise is observed at stations located close to the roads and structures (e.g,. PRDX).

Examples of the SH1 data from the short-period array are shown in Figure 5a. The waveform variation between the array elements are caused by the local site effects. Figure 5b shows the records for the calibration shot CA1. Notice the similarity between SH1 and CA1 waveforms, despite the two orders of magnitude yield and amplitude difference between the shots. The SNR for the calibration shots degrades significantly beyond the distance of 3–4 km.

A number of the permanent stations in New England recorded some or all of the shots from the GAS2016 experiment. The SNR is good at Lisbon, New Hampshire (LBNH, United States National Seismic Network; see Data and Resources) and low at most of other stations. LBNH waveforms are dominated by high-frequency *P*-wave coda with scattered secondary arrivals as shown in Figure 6.

SUMMARY

The active source explosion experiment was conducted in New Hampshire in August 2016. The purpose of the experiment was to study the seismic signatures of the explosion sources using different explosive types that generated different amounts of gaseous products. WGC collected seismic data from 45 stations located between 1.5 m and 9.4 km from the sources. Data from the experiment can be used for explosion-source studies, explosion monitoring, seismic-event detection, discrimination, and yield estimation. In addition, data from this and other explosion experiments, including the NEDE in Vermont (Martin *et al.*, 2012) and the Fracture Decoupling Experiment in New Hampshire (Stroujkova *et al.*, 2013), can provide ground-truth events for the crustal studies, and velocity calibration in New England.

DATA AND RESOURCES

Seismic data from GAS2016 were collected by Weston Geophysical Corp. A portion of the seismic instruments were provided by the Incorporated Research Institutions for Seismology (IRIS) through the Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center at New Mexico Tech. Data from short-period seismographs have been archived and submitted to the IRIS Data Management Center (DMC). The facilities of the IRIS Consortium are supported by the National Science Foundation under Cooperative Agreement EAR-1261681 and the DOE National Nuclear Security Administration. Data have been archived at IRIS DMC in PH5 format under assembled ID 16-017. Data collected will be available through webservices under FDSN network code Y3.2016-2016 (doi: http://dx.doi.org/10.7914/SN/Y3_2016; http://www.fdsn.org/networks/detail/Y3_2016/, last accessed June 2017). The data will remain under embargo until August 2018. After that date, data recorded by the short-period seismographs can be obtained from the IRIS DMC at www.iris.edu (last accessed November 2016) and http://ds.iris.edu/mda/ (last accessed June 2017). To access the data recorded by the near-source accelerometers contact James Lewkowicz (jiml@westongeo.com). Data from station LBNH and other regional stations (United States National Seismic Network, doi: http://dx.doi.org/10.7914/SN/US) is available from IRIS DMC at http://ds.iris.edu/ds/ (last accessed April 2017).

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